GROUND-WATER RESOURCES OF THE LOWER APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN IN PARTS OF ALABAMA, FLORIDA, AND GEORGIA—*SUBAREA 4* OF THE APALACHICOLA-CHATTAHOOCHEE-FLINT AND ALABAMA-COOSA-TALLAPOOSA RIVER BASINS

U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the

ALABAMA DEPARTMENT OF ECONOMIC AND COMMUNITY AFFAIRS OFFICE OF WATER RESOURCES

GEORGIA DEPARTMENT OF NATURAL RESOURCES ENVIRONMENTAL PROTECTION DIVISION

NORTHWEST FLORIDA WATER MANAGEMENT DISTRICT

U.S. ARMY CORPS OF ENGINEERS, MOBILE DISTRICT

Open-File Report 95-321

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1995**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Ground-Water Resources of the Lower Apalachicola-Chattahoochee-Flint River Basin in Parts of Alabama, Florida, and Georgia-Subarea 4 of the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa River Basins**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Department of the Interior 1849 C Street, NW Washington, DC 20240**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**145**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	43.81	liter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
part per million	1,000	microgram per liter (µg/L)
foot squared per day (ft^2/d)	0.0929	meter squared per day
foot per day (ft/d)	0.3048	meter per day

Sea Level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Acronyms

Apalachicola-Chattahoochee-Flint (ACF)

Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa (ACF/ACT)

MODular Finite-Element model (MODFE)

GROUND-WATER RESOURCES OF THE LOWER APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN IN PARTS OF ALABAMA, FLORIDA, AND GEORGIA—SUBAREA 4 OF THE APALACHICOLA-CHATTAHOOCHEE-FLINT AND ALABAMA-COOSA-TALLAPOOSA RIVER BASINS

By Lynn J. Torak *and* Robin John McDowell

ABSTRACT

The study area is underlain by Coastal Plain sediments of pre-Cretaceous to Quaternary age consisting of alternating units of sand, clay, sandstone, dolomite, and limestone that gradually thicken and dip gently to the southeast. The Upper Floridan aquifer is composed of an offlapping sequence of clastic and carbonate sediments consisting of the Clinchfield Sand, the Ocala, Suwannee, and Tampa Limestones, and the Marianna Formation. The Intermediate system consists of the Intracoastal, Chipola, and Jackson Bluff Formations, is limited in areal extent to the southern part of the basin in Florida, and constitutes an aquifer of low yield. The aquifer-stream-reservoir (flow) system is defined by surface water in hydraulic connection with aquifers and semiconfining units.

Simulation of the flow system by using the U.S. Geological Survey's <u>MOD</u>ular <u>F</u>inite-<u>E</u>lement model (MODFE) of two-dimensional ground-water flow indicated that ground-water availability in Alabama is affected most by changes to lateral and vertical boundary conditions to the Upper Floridan aquifer that might occur in that state, and is affected minimally by changes to ground- and surface-water levels in Georgia. Incomplete hydrologic information precludes definitive assessment of ground-water-resource potential, overpumpage, and potential for additional development; however, simulated-increased pumpage at more than 3 times the October 1986 rates caused drying of the Upper Floridan aquifer in parts of Miller and Lee Counties, Ga. Evaluation of ground-water-development potential in the virtually untapped Intermediate system has questionable reliability due to the lack of data.

Increased hypothetical pumpage over October 1986 rates for the Upper Floridan aquifer, located almost entirely in Georgia, indicated reduction in ground-water discharge to streams that reduced flow in the Apalachicola River and to the Bay, especially during droughts. Water budgets prepared from simulation results indicate that discharge to streams and recharge by horizontal and vertical flow are principal hydrologic mechanisms for moving water into, out of, or through aquifers. The Intermediate system contributes less than 2 percent of the total simulated ground-water discharge to streams; thus, it does not represent an important source of water for the Apalachicola River and Bay.

INTRODUCTION

The Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa (ACF/ACT) River Basins extend from the Georgia-Tennessee State line south and west to include about 42,000 square miles in Alabama, Florida, and Georgia. The river basins are located within parts of the Blue Ridge, Piedmont, Valley and Ridge, and Coastal Plain physiographic provinces. Eight subareas of the ACF/ACT River Basins have been identified on the basis of physiographic and hydrographic boundaries to facilitate investigation of river hydrology, surface water-aquifer interactions, and effects of pumpage on the aquifer-stream-reservoir system (fig. 1). This report focuses on the ground-water resources of Subarea 4: the lower ACF River Basin in southeastern Alabama, northwestern Florida, and southwestern Georgia.

Increased and competing demands for the limited surface- and ground-water resources of the lower ACF River Basin have caused concern to water managers in Alabama, Florida, and Georgia and at federal levels, and have become the object of difficult and sometimes conflicting management decisions. The basin's water resources emanate from a hydrosystem defined by an interconnected network of aquifers, streams, reservoirs and other control structures, flood plains, and estuaries. The high degree of hydrologic interaction among various components of this hydrologic system requires that a unified approach be adopted to understand and manage the water resources as a single, hydrologic entity. The rivers and their impoundments are used as a waterway for shipping, a source for hydropower generation, a fresh-water supply for agriculture and industry, and for recreational purposes. Apalachicola Bay supports an active and economically important shellfish industry that depends on a supply of nutrients to be carried to the Bay by fresh water from the Apalachicola River. The Apalachicola, Chattahoochee and Flint Rivers drain (in part) one of the most productive aquifers in the nation, the Upper Floridan aquifer; however, stream aquifer relations are not well understood. Ground-water withdrawal from the Upper Floridan aquifer and from other aquifer systems connected to the rivers potentially decrease the base flow of streams and, thus, reduce the amount of water available for storage in Lake Seminole, which subsequently supplies fresh water and nutrients to the Apalachicola River and Bay.

Recent drought conditions in the basin during 1969, 1980–81, and 1986–88 have brought attention to the many uses of surface- and ground-water supplies and to present and anticipated conflicts in water use resulting from extremely dry climatic periods. In 1984, the U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., (Corps) initiated a study with the States of Alabama, Florida, and Georgia to develop a water-management plan for the ACF River Basin. A major component of the overall study was the reinitiation of a study of the basin that originally was authorized for the Corps through the River and Harbor Act of 1927, in accordance with House Document No. 308, 69th Congress, and was termed the "308" study. The "308" study evaluated the feasibility of comprehensive development of water resources of specific river basins throughout the nation and investigated long-term solutions to the basins' water-resources problems (Lawrence R. Green, Mobile District, U.S. Army Corps of Engineers, Mobile, Ala., written commun., 1984). A result of the "308" study was the development of finite-element, digital-computer models of ground-water flow having stream-aquifer relations (Torak and others, 1996) for the flow systems comprised of the Upper Floridan aquifer and other water-bearing units that are connected hydraulically to surface water. The models developed by Torak and others (1996) focused on defining the ground-water component of streamflow and effects on the flow system of increased ground-water development during dry periods. The models were calibrated to historical-drought conditions of October 1986, which served as the basis for additional simulations that investigated flow-system sensitivity to changes in hydraulic characteristics and pumpage.

These investigations and recent water projects, resource reallocations, and other actions proposed by local, State, and Federal agencies heightened water-availability concerns and created new conflicts among the States of Alabama, Florida, and Georgia, and the Corps. The need to better understand the hydrodynamics of the aquifer-stream-reservoir system became apparent to scientists and water managers alike.

> "Recent proposals to develop water-resource projects and to revise operating practices
> in the Apalachicola-Chattahoochee-Flint (ACF) and the Alabama-Coosa-Tallapoosa (ACT)
> River basins have created controversy between water-user groups, the states, and various

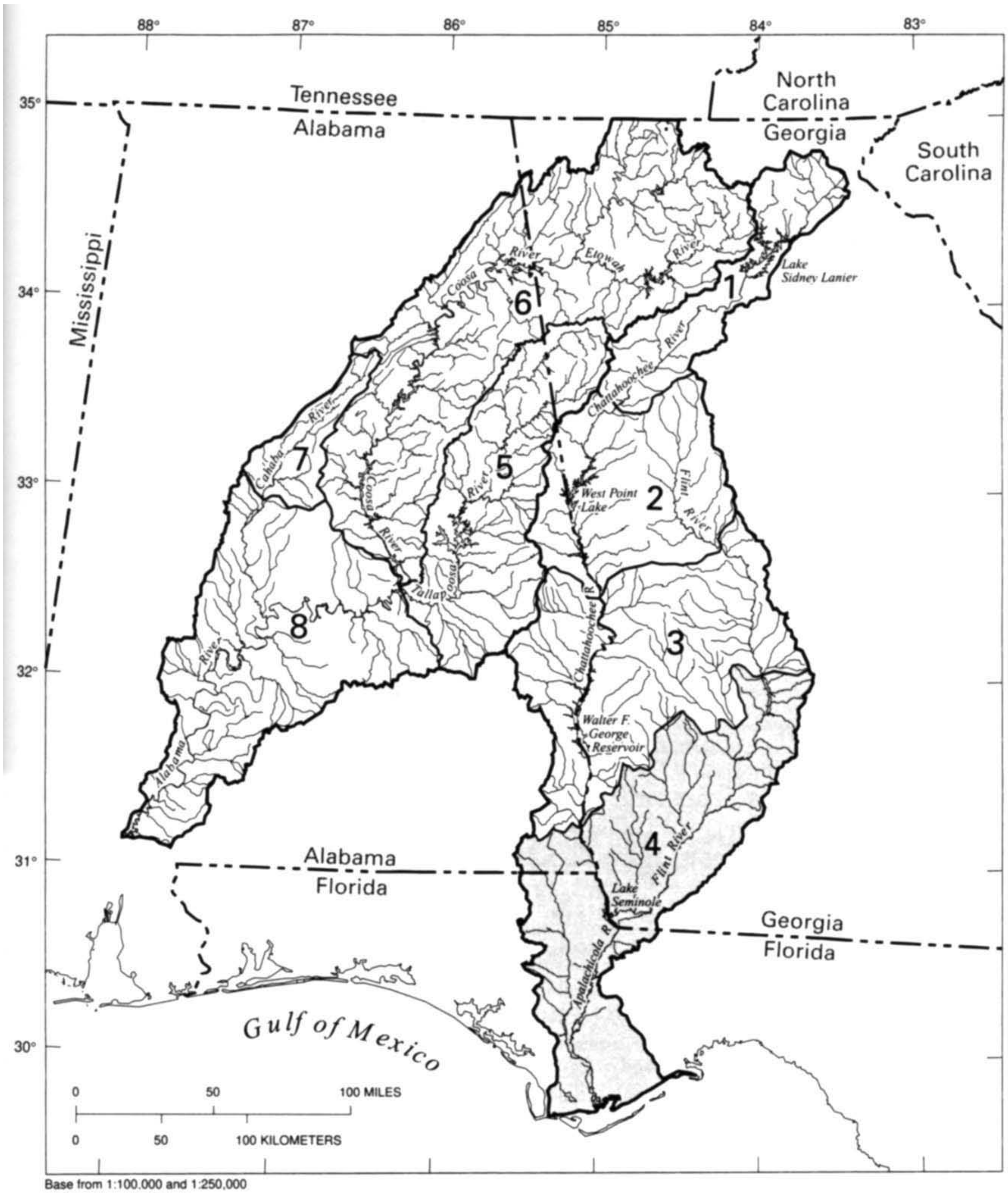

Figure 1. Location of subareas and major streams in the Apalachicola–Chattahoochee–Flint and Alabama–Coosa–Tallapoosa River Basins.

> federal agencies. Public responses to various reallocation proposals by the Corps were concerned with projected impacts to reservoir levels and downstream flows, interbasin transfers, cumulative impacts from water withdrawals, water quality, and concerns over the adequacy of environmental protection....To address these issues, Congress has funded a Comprehensive Study to develop the needed basin and water resource data and recommend an interstate mechanism for resolving issues,"

(excerpted from "Draft Plan of Study, Comprehensive Study, Alabama-Coosa-Tallapoosa and Apalachicola-Chattahoochee-Flint River Basins, Prepared By: The Comprehensive Study Technical Coordination Group, July 1991," U.S. Army Corps of Engineers, Mobile District, 48 p.).

In 1992, the Governors of Alabama, Florida, and Georgia and the Assistant Secretary of the Army for Civil Works signed a Memorandum of Agreement (MOA) establishing a partnership to address interstate water-resource issues and promote coordinated systemwide management of water resources. An important part of this agreement is the Comprehensive Study of the ACF and ACT River Basins. Since signing the MOA, the Study partners defined scopes of work designed to develop relevant technical information, strategies, and plans, and to recommend a formal coordination mechanism for the long term, basinwide management and use of water resources to meet environmental, public health, and economic needs (Comprehensive Study Newsletter, Spring 1993, U.S. Army Corps of Engineers, Mobile District). The U.S. Geological Survey (USGS) was selected as the principal contributor to the ground-water-supply element of the scope of work in the Comprehensive Study that addresses water-resources availability. Work began in June 1993.

Purpose and Scope

This report describes one aspect of a larger investigation (Comprehensive Study) of the effects of water-management practices on resource availability in the ACF/ACT River Basins. Specifically, the purpose of this report is to describe the ground-water resources of the lower ACF River Basin in southeastern Alabama, northwestern Florida, and southwestern Georgia (Subarea 4 of the ACF/ACT River Basin). This report addresses ground-water availability and its relation to surface water. Findings contained herein are but one component of a multidiscipline assessment of issues related to basinwide utilization and management of water. This report is not intended to give definitive answers regarding the acceptability of impacts from current ground-water-resource utilization or the potential for additional resource development. Such answers are dependent on the synthesis of results from the other Comprehensive Study components and from subsequent consideration by the State and Federal water managers responsible for decision making within the basins.

The following objectives of the Comprehensive Study of the ACF/ACT River Basins are addressed in this report:

- Qualitatively evaluate how changes in surface- and ground-water levels affect surface- and ground-water availability in Alabama
- Evaluate development potential of ground-water resources
- Develop water budgets to describe the volume of water entering and exiting the subarea that include processes such as recharge by precipitation and surface- and ground-water inflow and outflow
- Quantitatively determine how current and future ground-water withdrawals in southwestern Georgia and southeastern Alabama will affect surface-water flow to the Apalachicola River and Bay, particularly during critical low-flow periods such as droughts.

To meet these objectives, project tasks were performed using available technology and field data. No new technology was developed, no new field work was performed, nor any work undertaken that did not relate directly to water-resource evaluation. Thus, project tasks filled the following purposes of the study:

- Describe the hydrogeology and surface-water-flow system
- Evaluate ground-water resources and develop a conceptual model of the flow system
- Evaluate stream-aquifer relations through simulation

- Determine effects of pumpage, boundary conditions, and surface-water levels on the flow system through water-budget analysis,
- Test scenarios of potential ground-water development through simulation
- Evaluate development potential of ground-water resources on the basis of simulation results.

The study focuses on assessment of low flows as each principal river and aquifer conveys water from one hydrogeologic subarea to another or from one state to another. Critical information was obtained on understanding the “big picture” of how withdrawals in one subarea or state affect water availability in an adjacent subarea or state. Conceptual models describing hydrologic processes that govern ground-water and surface-water flow were prepared by using existing hydrogeologic, climatologic, and water-use information. Previously developed and calibrated digital models of the aquifer-stream-reservoir (flow) systems (Torak and others, 1996) based on a standardized computer program (MODFE; Cooley, 1992; Torak, 1993a,b) provided more accurate evaluation of stream-aquifer relations than would be possible by using only a conceptual model.

Of particular interest are the combined effects of simulating changes in ground-water pumpage and hydrologic boundaries of the Upper Floridan aquifer on streamflows and ground-water levels. Previous studies (Hayes and others, 1983; and Torak and others, 1993, 1996) indicated that the ground-water component of streamflow, or base flow, is affected by ground-water withdrawals; however, effects of multiple changes in hydrologic conditions were not addressed. Through simulation techniques, a range of ground-water-withdrawal rates and hydrologic conditions were used in this study to determine their effects on ground-water levels and flow to streams, including flow to the Apalachicola River and Bay.

Area of Study and Physiography

The lower ACF River Basin encompasses an area of about 6,800 mi^2 within the Coastal Plain physiographic province (fig. 2). The Coastal Plain is subdivided in Alabama, Florida, and Georgia into 4 districts: Fall Line Hills, Dougherty Plain, Tifton Upland, and Gulf Coastal Lowlands. Physiographic descriptions for subdivisions of the Coastal Plain province are given by Puri and Vernon (1964), Sapp and Emplaincourt (1975), Clark and Zisa (1976), and Brooks (1981), and are summarized briefly in this report. The northern extent of the lower ACF River Basin is located in the Fall Line Hills district at the updip limit of the Upper Floridan aquifer. The limestone is the principal water-bearing unit of the Upper Floridan aquifer and is drained by the Chattahoochee and Flint Rivers and their tributaries.

The Fall Line Hills district is a highly dissected series of ridges and valleys that diminish in relief to the south and east into lowlands of the Dougherty Plain (Wagner and Allen, 1984). The eastern limit of the lower ACF River Basin coincides approximately with the boundary between the Tifton Uplands and the Dougherty Plain districts and the Gulf Coastal Lowlands district occupies the southern part of the basin. The western basin boundary is defined by ground-water and surface-water divides within the Dougherty Plain and Gulf Coastal Lowlands districts. The southern limit of the basin is the Gulf of Mexico.

The Dougherty Plain district is an inland lowland comprised of a series of nearly level plains (Hicks and others, 1987). Relief within most of the Dougherty Plain rarely exceeds 20 ft. In the Florida panhandle, the Dougherty Plain district includes the Marianna Lowlands described by Puri and Vernon (1964) (fig. 3).

The Dougherty Plain is characterized by karst topography having numerous sinkholes (shallow, circular depressions) ranging in size from a few feet to several hundred acres. Most depressions are filled with low-permeability material and some contain water year round (Middleton, 1968). Active solutioning of Ocala Limestone in the Dougherty Plain has created underground channels that capture surface drainage; only larger streams flow in terraced valleys (Hicks and others, 1987).

A steeply sloping, west-facing karst area named the Solution Escarpment by MacNeil (1947), or Pelham Escarpment (Hayes and others, 1983), separates the Dougherty Plain from the Tifton Uplands district (fig. 2).

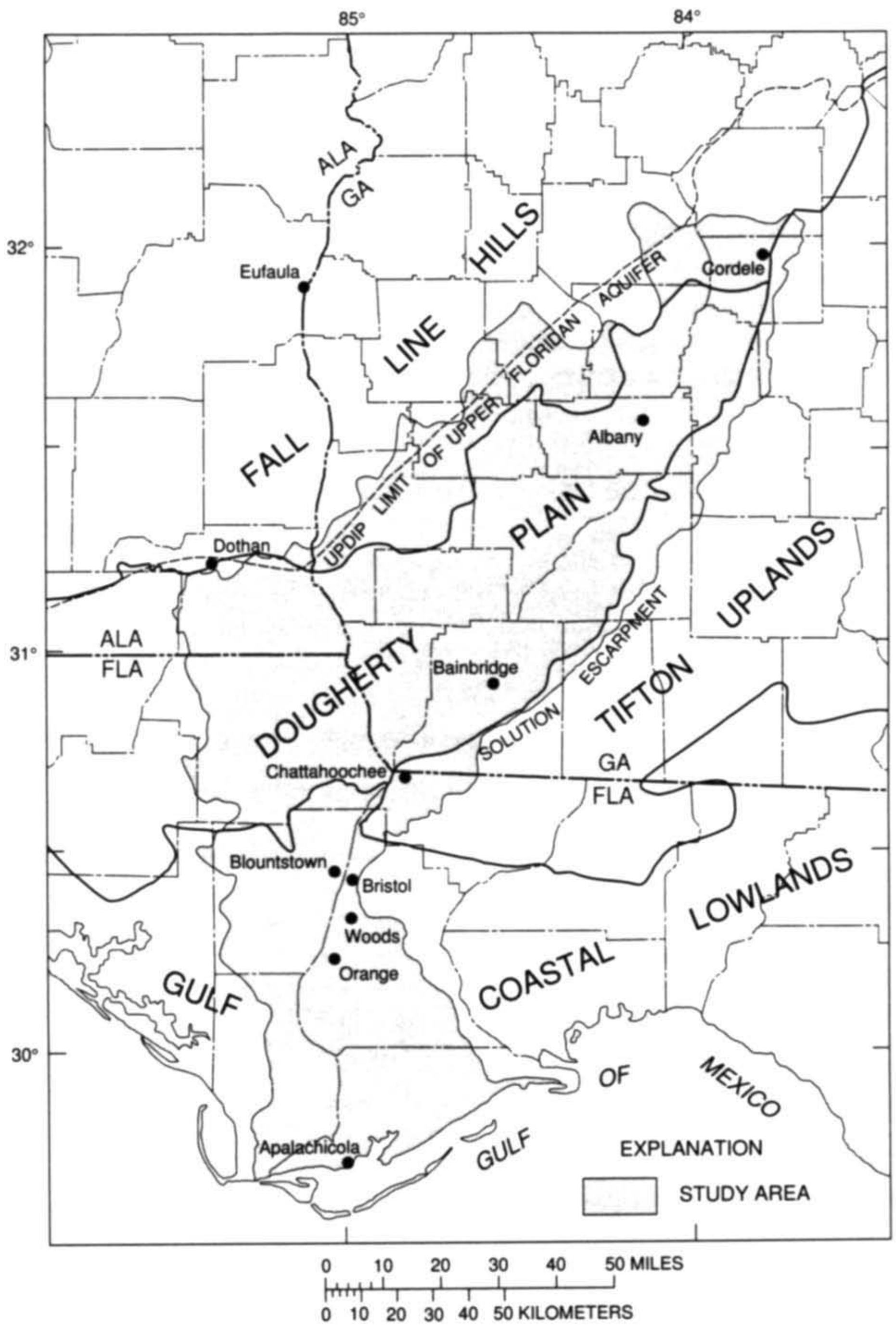

Figure 2. Location of study area, boundaries of the lower Apalachicola–Chattahoochee–Flint River Basin, and physiographic divisions of the Coastal Plain province in southeastern Alabama, northwestern Florida, and southwestern Georgia (from Torak and others, 1996).

The crest of the Solution Escarpment forms the topographic and surface-water divide between the Flint River basin and the Ochlockonee and Withlacoochee River Basins to the east.

East of the Solution Escarpment lie the narrow, rounded plateaus and well-developed drainage patterns of the Tifton Upland, termed the Tallahassee Hills in north Florida (fig. 3) (Puri and Vernon, 1964; White, 1970). This is a region of high hills composed largely of resistant clayey sands, silts, and clays (Arthur and

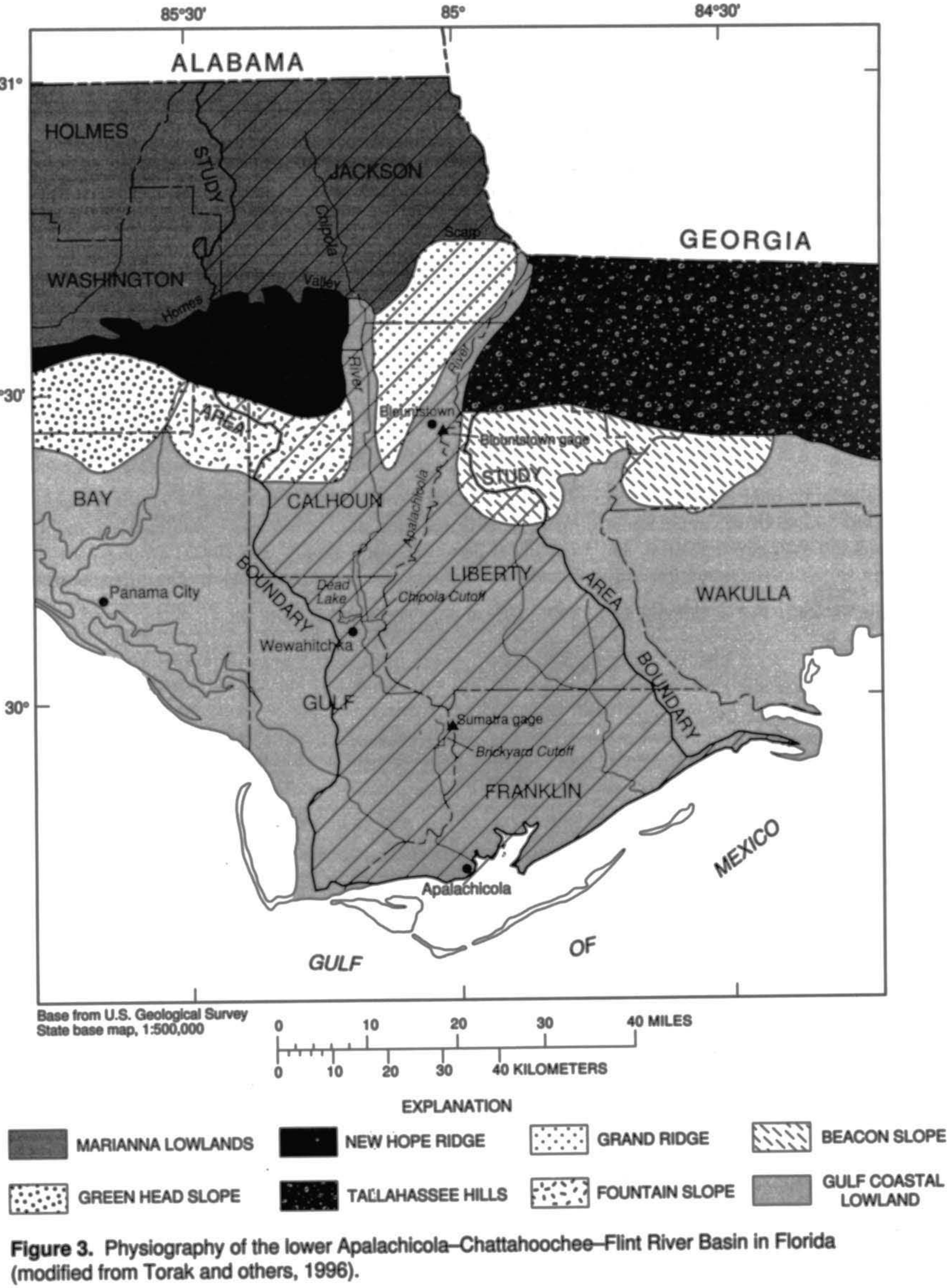

Figure 3. Physiography of the lower Apalachicola–Chattahoochee–Flint River Basin in Florida (modified from Torak and others, 1996).

Rupert, 1989). The Tallahassee Hills end abruptly at the Apalachicola River in steep bluffs 150 to 200 ft above the flood plain and expose sediments of Miocene to Holocene age.

West of the Tallahassee Hills lie the Grand Ridge and New Hope Ridge regions (fig. 3), a series of remnant hills and sand-hill ridges dissected by stream valleys (Puri and Vernon, 1964). The Grand Ridge and New Hope Ridge regions are bounded to the north by the Holmes Valley Scarp (fig. 3), a prominent topographic feature that separates these ridges from the Marianna Lowlands.

South of the New Hope Ridge and Tallahassee Hills, the Fountain Slope and Beacon Slope (fig. 3) (Puri and Vernon, 1964) are characterized by uniformly sloping topography and swampy depressions and sinks where surface sediments overlie karst terrane (Arthur and Rupert, 1989). Along the northern boundary, the Beacon Slope is separated from the Tallahassee Hills by the Cody Scarp (fig. 3).

The Gulf Coastal Lowlands are characterized by a sandy, flat, seaward-sloping feature shaped mostly by wave and current activity during Pleistocene high sea-level stands (Arthur and Rupert, 1989). The land surface is characterized by relic marine bars, spits, and sand-bar dunes (fig. 3), and by marine terraces of Pleistocene age.

Ground-Water Use

The total amount of ground water used in Subarea 4 during 1990 was about 224.72 Mgal/d (Marella and others, 1993). Of this total, about 66 percent is agricultural use; 21 percent is public-water supply; 8 percent is self-supplied industrial, and 5 percent is domestic-water supply. The largest ground-water use in Alabama is public-water supply, and in Florida and Georgia, the largest ground-water use is agriculture.

Ground-water use in Subarea 4 for 1990, by category and state, is as follows:

Ground-water use by state, in million gallons per day					
State	**Public-water supply**	**Self-supplied industrial and commercial**	**Agricultural**	**Domestic**	**Total**
Alabama	13.49	0.41	9.2	1.31	24.41
Florida	5.04	2.55	25.53	5.2	38.32
Georgia	28.81	15.30	113.71	4.16	161.99
Subarea total	47.34	18.27	148.44	10.67	224.72

Methods of Investigation

Methods used to evaluate stream-aquifer relations in the lower ACF River Basin include acquisition, assimilation, and interpretation of existing geologic and hydrologic information pertaining to aquifers in contact with surface-water features, measurements of ground- and surface-water levels, streamflow, base-flow estimates of streams, and numerical simulation. Much of this information, including well logs, geologic sections, maps of potentiometric surfaces, tables of hydrologic information, and records of wells drilled in the basin was available from a variety of published and unpublished sources at local, State, and Federal agencies and was used to develop a conceptual model of the stream-aquifer system.

Measurements of ground- and surface-water levels and streamflow that were taken during extremely dry conditions in late-October 1986 existed in files at the USGS District Office, Atlanta, Ga. These values repre-

sented a network of 303 wells tapping the Upper Floridan aquifer and other aquifer systems that are connected hydraulically with surface water (pl. 1). Streamflow from 94 locations were used to estimate base flow along 37 reaches of streams within the basin.

Numerical simulation of ground-water flow in the stream aquifer system was performed by using the USGS's MODular Finite Element model (MODFE) for ground-water flow in two dimensions (Cooley, 1992; Torak, 1993a,b). This model contains mathematical representations of hydrologic processes that were conceptualized as controlling ground- and surface-water flow in the lower ACF River Basin. Stream aquifer relations are quantified in MODFE by computed leakage rates across streambed aquifer boundaries and water budgets for selected reaches and the entire study area. Calibrated, steady-state models of the aquifer-stream-reservoir (flow) systems that were developed by Torak and others (1996) were used in steady- and nonsteady-state simulations for this study. The simulations represented historical, "dry" conditions of October 1986 and long-term-average, "normal" conditions for ground- and surface-water levels, which form boundary conditions to the aquifers, and changes to the rates of ground-water pumpage for October 1986.

Previous Studies

Numerous studies of the geology, hydrology, and ground-water resources of the lower ACF River Basin have been made since the earliest publication in the late 1890's. Most of these studies, however, give hydrologic details only in areas of greatest ground-water withdrawals. Outside of these areas, limited hydrologic information about aquifers and stream-aquifer relations is available from general-reconnaissance studies.

General descriptions of the geology and ground-water resources of the Coastal Plain have been given by McCallie (1898), Stephenson and Veatch (1915), Cooke (1943) and Herrick (1961). The hydrogeology of southwestern Georgia has been described in reports by Wait (1963), Sever (1965a, 1965b), Pollard and others (1978), Hicks and others (1981, 1987), Hayes and others (1983), and Torak and others (1993). In Alabama, reports by Scott and others (1984), Moffett and others (1985), and Moore and Moser (1985) provide useful background information on geology, hydrology, and water resources. Studies in Florida by Moore (1955), Kwader and Schmidt (1978), Schmidt (1978, 1979, 1984), Schmidt and Clark (1980), and Schmidt and others (1980) describe the geology of parts of the lower ACF River Basin, and Arthur and Rupert (1989) give details about basin physiography.

A study by Torak and others (1993) described hydrogeology and evaluated water-resource potential of the Upper Floridan aquifer in the Albany area, southwestern Georgia. Two water-bearing units of the aquifer in contact with major surface-water features were identified from hydrogeologic information obtained for this study. Detailed information on fractures, and solution features, and hydraulic properties of the Upper Floridan aquifer was compiled and results were incorporated into a finite element model of two-dimensional ground-water flow. Model analysis indicated that ground-water pumpage intercepts less than 10 percent of the regional flow of ground water that would otherwise discharge to the Flint River, which is the principal, natural drain to the aquifer in the Albany area. Other model results indicated that ground-water levels are affected minimally by pumpage in the Upper Floridan aquifer and by changes in stage of the Flint River, and that ground-water resources of the aquifer tend to be controlled by large regional-flow components.

Another study by Torak and others (1996) laid the hydrogeologic and numerical groundwork for much of the work presented in this study. Their study, conducted under the auspices of the "308" study mentioned previously, gave hydrogeologic descriptions of the aquifer-stream-reservoir systems containing the Upper Floridan aquifer and other water-bearing units in the lower ACF River Basin, conceptualized flow in these systems, and simulated steady-state ground-water flow with stream-aquifer relations for drought conditions of October 1986. Simulation results indicated a definite reduction of stream-aquifer flow (ground-water component of streamflow) due to increased pumpage at multiples of the October 1986 rates that range from 2 to 7, and a moderate sensitivity of the flow system to changes in hydraulic heads that control leakage rates across lateral- and vertical-flow boundaries, including changes in stream stage. The calibrated finite-element models

developed in that study were used here to test the effects on the flow system of hydrologic conditions other than those of October 1986.

Two additional studies used simulation techniques to evaluate ground-water resources in parts of the lower ACF River Basin, but the objectives, purposes, and limitations of these studies precluded them from addressing stream-aquifer relations in the manner that is presented here. One of these studies (Maslia and Hayes, 1988) examined ground-water flow and recharge-discharge mechanisms of the Floridan aquifer in southwestern Georgia, northwestern Florida, and southernmost Alabama. Their report gives general descriptions of the predevelopment-flow system and detailed descriptions of the hydrogeology and flow system of 1980 in the Dougherty Plain and near Fort Walton Beach, Fla., which is west of the present study area. The other study (Bush and Johnston, 1988) applied simulation techniques to the lower ACF River Basin as part of the USGS's Regional Aquifer Systems Analysis (RASA) program. It defined general, regional-scale ground-water-flow characteristics of the entire Floridan aquifer system within the southeastern Coastal Plain of Florida, southern Georgia, South Carolina, and Alabama. As a regional study, it did not address details of stream aquifer relations at a local scale.

During 1979–81, the USGS conducted a large-scale study of the Apalachicola River, termed the Apalachicola River Quality Assessment. A series of reports (Elder and Cairns, 1982, Elder and others, 1984; Leitman and others, 1984; and Mattraw and Elder, 1984) describe hydrologic and ecologic investigations made for the Assessment. Water and nutrient budgets based on data collected during that study indicate the relative importance of inputs and outflows in the system, such as streamflow, total nutrient inflow and outflow, flood-plain forest, and the role of the flood plain in yielding nutrients and detritus to the Apalachicola River estuary (Elder and others, 1984).

As part of the study with the States of Alabama, Florida, and Georgia, the U.S. Army Corps of Engineers, Mobile District, Mobile, Ala., completed the "1984 Water Assessment" (U.S. Army Corps of Engineers, States of Alabama, Florida, and Georgia, 1984) of the entire ACF River Basin. This study was limited to available data and consisted of a main report and 6 appendixes that address the following topics of concern in the basin: natural environmental setting, economic setting, water resources (surface and ground water), water use and availability, water quality, water-management setting, and problem areas and current solution efforts. As part of the study's conclusions and recommendations, the Corps identified deficiencies in the type of information required for managing water resources in the basin. Most notable deficiencies are those of quantifying stream-aquifer relations and in determining present and future water needs for multiple uses of the basin, such as navigation, ground-water pumpage for irrigation, and fresh-water supply to Apalachicola Bay.

Well- and Surface-Water Station Numbering System

Wells used in this report are numbered for identification purposes according to several conventions. Wells located in Alabama are identified by 3 digits prefixed by the letters "ALA", such as ALA001. Wells located in Florida are identified by 3 digits prefixed by a 3-letter, county code, such as JAC001 for a well in Jackson County. The other county codes and corresponding counties (in parentheses) are as follows: CAL (Calhoun), FRA (Franklin), GAD (Gadsden), GUL (Gulf), and LIB (Liberty).

Wells in Georgia are numbered by a system based on USGS topographic maps. Each 7½ minute topographic quadrangle map in Georgia has been given a number and letter designation beginning at the southwest corner of the State. Numbers increase eastward through 39; letters advance northward through "Z," then double letter designations "AA" through "PP" are used. The letters "I, O, II, and OO" are not used. Wells inventoried in each quadrangle are numbered sequentially beginning with "1." Thus, the 48th well inventoried in the Albany West quadrangle (designated 12L) in Dougherty County is designated 12L048.

Partial and continuous-record surface-water stations are given a station-identification number, which is assigned according to "downstream-order" (Stokes and others, 1990). No distinction is made between

partial-record stations and other stations; therefore the station number for a partial-record station indicates downstream order position in a list made up of both types of stations. The complete number for each station includes a 2-digit Part number “02” plus the downstream-order number, which can be from 6 to 12 digits. In this report, the Part number is omitted; only the 6-digit downstream-order number is used.

Acknowledgments

The authors extend appreciation to all those who contributed valuable hydrogeologic information and interpretations about the ground-water-flow system in the lower ACF River Basin. In particular, sincere appreciation is given to Jeffry Wagner, formerly of the Northwest Florida Water Management District, Havana, Fla., and to Frank Rupert and Walter Schmidt of the Florida Bureau of Geology, Tallahassee, Fla.

HYDROGEOLOGY

Brief summaries of lithologic characteristics and their hydrologic implications to the stream-aquifer relations in the study area are presented here. More detailed descriptions and discussions of regional stratigraphic relations can be found in the previous report by Torak and others (1996), which was prepared for the “308” study of the lower ACF River Basin and is the basis for the contents of this section.

Geologic Setting

The study area is underlain by Coastal Plain sediments of pre-Cretaceous to Quaternary age consisting of alternating units of sand, clay, sandstone, dolomite, and limestone that dip gently, and generally thicken, to the southeast (Hicks and others, 1987). Only geologic units pertinent to the functioning of the flow system defined by aquifers and semiconfining units in contact with surface-water bodies were considered in this study. In Alabama, these units constitute sediments that range in age from late-middle Eocene to Holocene and are, in ascending order, the Lisbon Formation, undifferentiated Ocala Limestone and Moodys Branch Formation (combined in this report and henceforth termed Ocala Limestone), undifferentiated overburden, and terrace and undifferentiated (alluvial) deposits.

In Florida and Georgia, sediments of late-middle-Eocene age and younger comprise the stream-aquifer system of interest to this study. These are, in ascending order, the Lisbon Formation, Clinchfield Sand, Ocala Limestone, Marianna Formation, Suwannee Limestone, Tampa Limestone, undifferentiated overburden, Intracoastal, Hawthorn, Chipola, Jackson Bluff, and Citronelle Formations, and terrace and undifferentiated deposits.

Geologic units are combined with regard to hydraulic properties and their function in the flow system to define hydrologic units. The hydrologic units serve either as aquifers, namely the Upper Floridan aquifer and Intermediate system, or as confining or semiconfining units in the flow system. At some locations, the semiconfining units provide ground-water recharge to, or discharge from, the aquifers. Hydrologic and stratigraphic relations in the study area in Florida and Georgia are shown in figure 4. In Alabama, the Upper Floridan aquifer consists of the Clinchfield Sand, where present, and the Ocala Limestone.

The Lisbon Formation consists of interbedded calcareous, glauconitic sand; sandy clay; and clay that crop out north of the study area in southeastern Alabama and southwestern Georgia (Miller, 1986). Within the study area in Florida and Georgia, the Lisbon Formation is thick and dense and serves as a lower, or sub-Floridan confining unit, representing a nearly impermeable base to the overlying Upper Floridan aquifer. In Alabama, the Lisbon Formation is the principal water-bearing zone of the Lisbon aquifer, or shallow aquifer system of Alabama, which includes the overlying Ocala Limestone and underlying sediments (Wagner and Allen, 1984). However, stratigraphic relations of the Lisbon Formation to the Ocala Limestone and geologic

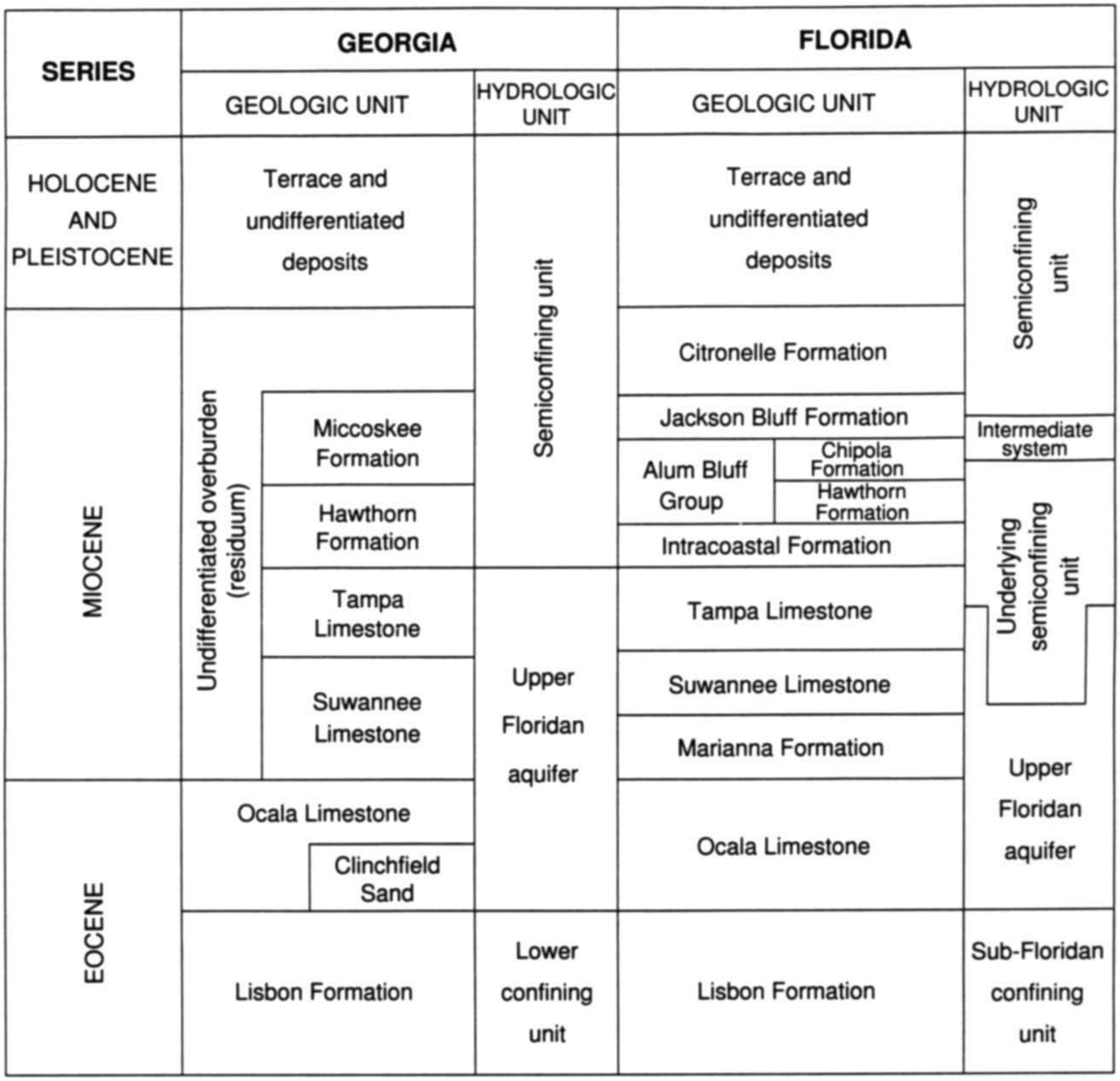

Figure 4. Correlation chart of stratigraphic and hydrologic units in the lower Apalachicola–Chattahoochee–Flint River Basin (from Torak and others, 1996).

processes involving the overlying units cause the Lisbon Formation to have a negligible influence on stream-aquifer relations in the Alabama part of the study area, as explained further in this section.

The Clinchfield Sand overlies the Lisbon Formation and crops out less than a mile beyond the updip limit of the overlying Ocala Limestone (Herrick, 1972). The Clinchfield Sand is an ancient beach deposit and generally consists of medium-to-coarse, fossiliferous, calcareous quartz sand. Downdip the sand grades into the Ocala Limestone (Herrick, 1972).

The Ocala Limestone overlies the Lisbon Formation and the Clinchfield Sand, where present, and consists of 2 different rock types that create 2 distinct flow regimes. The first flow regime is an upper unit of white, friable, porous coquina loosely bound by a matrix of micritic limestone, and the second is a lower unit of fine-grained, soft to semi-indurated, micritic limestone (Miller, 1986). In the Albany, Ga., area, the lower

unit is generally a recrystallized dolomitic limestone that can be very hard, but fractured (David W. Hicks, USGS, Atlanta, Ga., written commun., 1994). The upper part of the Ocala Limestone functions primarily to supply ground water to the lower part of the unit, which contains most of the lateral ground-water flow in the Upper Floridan aquifer (Torak and others, 1993). In the southeastern part of Houston County, Ala., the Ocala Limestone thickens to about 300 ft (pl. 3). Locally, the upper few feet of the Ocala in the subsurface consists of soft, clayey residuum (Miller, 1986).

The Marianna Formation and the Suwannee Limestone crop out in south-central Jackson County, Fla. The Marianna Formation is more massive and chalky than the Ocala Limestone and pinches out downdip where it is overlain by the Suwannee Limestone (Schmidt and Coe, 1978; Schmidt, 1984). The Suwannee Limestone is exposed in scattered sinkholes and road cuts near the base of the Solution Escarpment (Hicks and others, 1987). The Marianna Formation and Suwannee Limestone consist of soft, chalky, biomicritic limestone (Wagner and Allen, 1984). Dissolution has produced numerous interconnected solution openings in the upper few feet of the Suwannee exposure. The solution openings function to supply water to the underlying Ocala Limestone. Downdip, the Tampa Limestone overlies the Suwannee Limestone.

The Tampa Limestone crops out in southern Jackson County, Fla., and in Decatur County, Ga. The Tampa Limestone is a white to light-gray, sandy, hard to soft, locally clayey, fossiliferous limestone (Miller, 1986). West of the Apalachicola River in southern Jackson and northern Calhoun Counties, Fla., the Tampa Limestone is well dissected by surface-water features and is not as areally extensive as it is east of the river. The Tampa Limestone east of the river contains beds of carbonate muds and clays interspersed with the limestone throughout its thickness (Jeffry Wagner, formerly of Northwest Florida Water Management District, Havana, Fla., written commun., 1987). Subsurface data indicate the existence of a dense, greenish-olive, waxy, clay or mixed, clay-limestone layer near the base of the Tampa Limestone, east of the river in Gadsden and northern Liberty Counties, Fla. This clay layer and the overall low permeability of the Tampa Limestone confines the underlying limestones of the Upper Floridan aquifer and impedes downward movement of water. Downdip, the Tampa Limestone is overlain by the Intracoastal, Hawthorn, Chipola, and Jackson Bluff Formations (fig. 4).

Undifferentiated overburden and alluvial deposits consisting of alternating layers of sand, silt, and clay, overlie and semiconfine the Upper Floridan aquifer. The lower half of the overburden contains higher percentages of clay than the upper half, and the upper half contains more sandy deposits than the lower half. The lower clayey overburden is probably residuum derived from weathering of the underlying limestone (Hayes and others, 1983; Hicks and others, 1987) and is responsible for semiconfining the aquifer. Where present, the upper, sandy part may contain a water table, which interacts with the Upper Floridan aquifer.

The Intracoastal Formation is a sandy, highly microfossiliferous, poorly consolidated, argillaceous, calcarenitic limestone (Schmidt, 1984; Schmidt and Clark, 1980) that can transmit small quantities of water. It overlies the Tampa Limestone south of central Calhoun County, Fla. In the southern part of the study area in Liberty, Gulf, and Franklin Counties, Fla., a dark gray, dense, plastic, dolosilt in the Intracoastal Formation inhibits vertical movement of water between the Upper Floridan aquifer and the Intermediate system and semiconfines the deeper unit.

The Chipola and Hawthorn Formations overlie the Intracoastal Formation throughout most of its areal extent in the ACF River Basin. It is a moderate- to well-indurated sandy, fossiliferous limestone that can also transmit small quantities of water. The Chipola Formation crops out north of Bristol, Fla., in Liberty County, Fla. Downdip, the Chipola is sporadically thinner and is absent at some locations (Schmidt, 1984).

The Jackson Bluff Formation overlies either the Chipola Formation, Intracoastal Formation (Wagner and Allen, 1984), Tampa Limestone, or Hawthorn Formation, depending on which unit is present. The Jackson Bluff Formation consists of 3 clayey, sandy, shell beds (Schmidt, 1984; Puri and Vernon, 1964) and crops out in southern Jackson and Gadsden Counties, Fla. In southern Liberty, Gulf, and Franklin Counties, Fla., the Jackson Bluff Formation is separated from overlying sands by clay beds (Wagner and Allen, 1984). Although part of the Intermediate system, the Jackson Bluff Formation and overlying clay beds semiconfine the deeper water-bearing units of the Intermediate system and impede the vertical movement of water.

Surficial deposits of the Citronelle Formation, terrace deposits, and undifferentiated sediments, overlie the Jackson Bluff Formation throughout its areal extent. The Citronelle Formation consists of fluvial, crossbedded sand, gravel and clay (Schmidt, 1984). Terrace deposits generally consist of unconsolidated, poorly sorted quartz sands that locally contain seams of clay (Wagner and Allen, 1984). Recent alluvium and undifferentiated deposits are prominent at and near the rivers in the study area.

Hydrologic Setting

Karst processes in the Dougherty Plain have established a highly active flow system in the Ocala Limestone that is characterized by high rates of direct ground-water recharge through sinkholes, swallow holes, or other circular depressions, indirect recharge by vertical leakage through the overburden, and discharge to surface water, such as the Chattahoochee River and headwater streams of the Chipola River. Thus, only geologic units younger than and including the Ocala Limestone were assumed to comprise the stream-aquifer system of importance to the study.

The Upper Floridan aquifer is comprised of the offlapping sequence of carbonate sediments consisting of the Ocala, Suwannee, and Tampa Limestones, Marianna Formation, and the Clinchfield Sand, where present (fig. 4). The older sediments extend to the surface in the northern outcrop area, and successively younger sediments are exposed to the south. Where they near the surface, such as in Alabama and Georgia, and in Jackson, Gadsden, northern Calhoun, and northern Liberty Counties, Fla., the limestones are semiconfined from above by undifferentiated overburden and by terrace and undifferentiated (alluvial) deposits. In the lower ACF River Basin, the Upper Floridan aquifer consists primarily of the Ocala Limestone. To the east and southeast of the Dougherty Plain, at the Solution Escarpment and in the Tifton Uplands (fig. 2), the aquifer includes the Suwannee Limestone.

The Intermediate system is contained entirely in Florida and consists of the Intracoastal, Chipola, and Jackson Bluff Formations (fig. 4), described in detail by Schmidt (1984) and by Wagner and Allen (1984). The Intermediate system is primarily a semiconfining unit to the underlying limestones of the Upper Floridan aquifer; however, locally sandy or carbonate beds of the Intracoastal and Chipola Formations constitute an aquifer and yield water to a few domestic wells. The Intermediate system and overlying terrace and undifferentiated deposits are connected to surface water in the southern part of the study area, thus stratigraphically and hydrologically replacing the Upper Floridan aquifer in stream-aquifer relations.

Surficial deposits of the Citronelle Formation, terrace deposits, and undifferentiated sediments contain a shallow water table where the deposits are medium to coarse grained. The fine-grained and clay-sized deposits create a semiconfining unit that impedes vertical leakage of water between the shallow water table and the underlying Intermediate system.

Hydrologic Characteristics

Variations in hydrologic characteristics of thickness and hydraulic conductivity distinguish the ability of the geologic units to function as aquifers and to transmit usable amounts of ground water for consumption, or to provide a mechanism for vertical leakage between aquifers and surface water, or between aquifers and source beds that are situated within and are separated by semiconfining units. The areal and vertical distribution of these hydrologic characteristics defines a complex flow system that makes for equally complex hydrodynamics of the aquifer-stream-reservoir system.

Overlying Semiconfining Units

In the lower ACF River Basin in Alabama, Georgia, and the northern panhandle of Florida, semiconfining units consisting of alternating layers of sand, silt, and clay overlie the Upper Floridan aquifer. In Alabama, Georgia and Jackson County, Fla. the semiconfining unit overlying the Upper Floridan aquifer is the

undifferentiated overburden. In Gadsden and northern Liberty Counties, Fla., the Upper Floridan aquifer is semiconfined by a clay bed at the base of the Tampa Limestone. In northern Calhoun County, Fla., the semiconfining unit consists of the Jackson Bluff Formation and overlying surficial deposits.

South of central Calhoun County, Fla., the Intermediate system is semiconfined above by overlying surficial deposits and clay beds in the Jackson Bluff Formation. In most places, the surficial deposits also contain sand, which maintains a water table. Hence, water is transmitted by vertical leakage to, or from, the semiconfining unit, providing recharge to, or discharge from, water-bearing units of the Intermediate system.

The dominant lithologic factor that controls hydraulic conductivity of the semiconfining unit overlying the Upper Floridan aquifer is the sand and clay content (Hayes and others, 1983). Vertical hydraulic conductivity of sediments in the overburden generally range from about 0.0004 ft/d for a silty clay to about 23 ft/d for a fine to medium sand (C.A. Turner, Soil & Material Engineering, Inc., written commun., 1988). Regional values of vertical hydraulic conductivity were estimated to range from 0.0001 to 9 ft/d, having a median value of 0.003 ft/d (Hayes and others, 1983).

Well data on file at the USGS, District Office, Atlanta, Ga., and the Florida Bureau of Geology, Tallahassee, Fla., indicate that overburden thickness generally ranges from about 20 to about 150 ft; however, the overburden can be locally absent, or its thickness can exceed 200 ft. A layer of clay is described in most lithologic logs that might be areally extensive and continuous throughout the lower half of the overburden. The clay layer at the base of the Tampa Limestone in Gadsden and Liberty Counties, Fla., is about 50-ft thick. Thickness of the Jackson Bluff Formation and the surficial deposits generally ranges from about 20 ft, near the outcrop of the Jackson Bluff Formation, to about 120 ft near the Gulf. Clay is dominant throughout the semiconfining units and confines the underlying aquifer.

Zones of equal thickness for the predominantly clayey sediments (pl. 2) were defined from these data and used in conjunction with vertical hydraulic conductivity to determine values of hydraulic conductance (vertical hydraulic conductivity divided by aquifer thickness). Vertical-hydraulic-conductance zones were used as input to the finite-element model (see “Conceptualization of the Flow System”). To facilitate input, zone boundaries were located approximately with element sides of the finite element mesh.

The relatively low vertical hydraulic conductivity and substantial thickness of the laterally continuous clay layer in the overlying semiconfining units create a hydrologic barrier to vertical flow of ground water to and from the aquifers. The clay layer can have a critical affect on ground-water flow in the aquifer system, causing perched ground water following periods of heavy rainfall, decreasing recharge of water to the aquifer by infiltration of precipitation, and controlling the rate of infiltration of chemical constituents from surface or near-surface sources that have the potential to contaminate ground water.

Intermediate System

The Intermediate system generally ranges in thickness from about 20 ft in Jackson County, Fla., where it consists of the Jackson Bluff Formation, to more than 300 ft near the Gulf. Water-bearing units of the Intermediate system range in thickness from about 30 to 250 ft and are mostly contained in the Chipola Formation (fig. 5). Ground-water flow in the Intermediate system is semiconfined below by a massive, plastic, dolosilt at the base of the Intracoastal Formation, and above by the Jackson Bluff Formation.

The aquifer of the Intermediate system has low permeability. Yields to domestic wells average about 5 gallons per minute (Wagner and Allen, 1984). Estimated transmissivity ranges from about 400 to 4,000 ft^2/d.

Underlying Semiconfining Unit

The semiconfining unit at the base of the Intermediate system south of central Calhoun County, Fla., (fig. 3) is a massive, clayey, dolosilt which confines the underlying Upper Floridan aquifer. Thickness of the clay bed generally ranges from about 5 to 30 ft. As with the overlying unit, zones of equal thickness for the

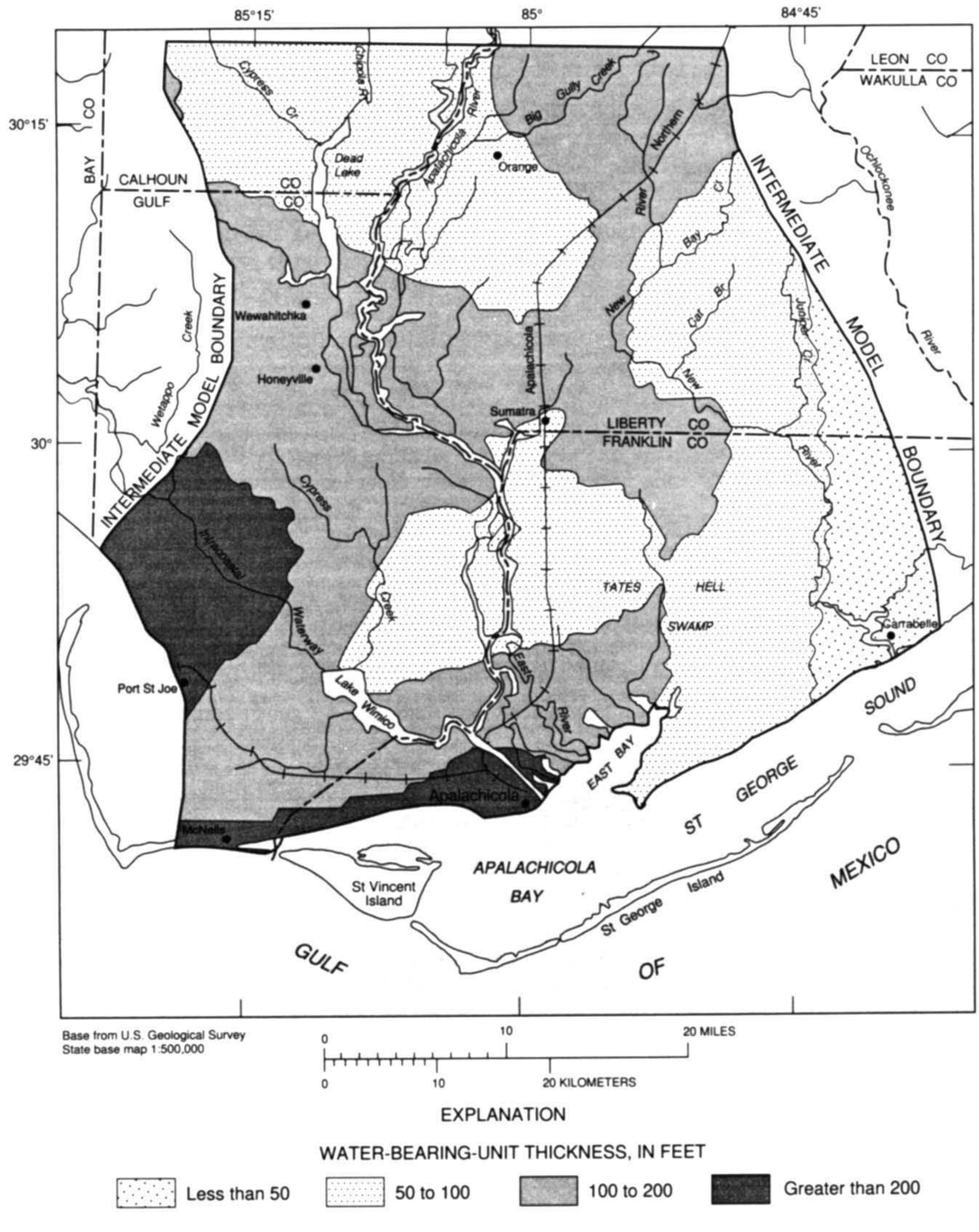

Figure 5. Thickness of water-bearing units in the Intermediate system (from Torak and others, 1996).

predominantly clayey sediments (fig. 6), were used in conjunction with values of vertical hydraulic conductivity to determine hydraulic conductance. Vertical-hydraulic-conductance zones were used as input to the finite-element model (see “Conceptualization of the Flow System”). To facilitate input, zone boundaries were located approximately with element sides of the finite element mesh.

Upper Floridan Aquifer

The Upper Floridan aquifer generally ranges in thickness from a few feet at the updip limit to more than 700 ft in Florida (pl. 3). The aquifer is confined below by low permeability sediments of the Lisbon Formation, and generally is semiconfined above by the undifferentiated overburden to the north. The aquifer is exposed along sections of major streams such as the Apalachicola, Chattahoochee, and Flint Rivers, and Spring Creek, where erosion has removed the overburden (Maslia and Hayes, 1988).

The capacity of the Upper Floridan aquifer to store and transmit large quantities of water is attributed to the fractured nature of the Ocala Limestone (Hayes and others, 1983) and associated dissolution of limestone by ground water circulating along bedding planes and fractures, and interconnected conduits or solution openings (Hicks and others, 1987). A system of major solution conduits between the Solution Escarpment and the Flint River transmits large quantities of ground water from the Upper Floridan aquifer to springs that discharge to the river. Solution conduits transmit a major part of the ground-water flow and contribute greatly to shaping the potentiometric surface of the aquifer (Hayes and others, 1983 p. 46). Consequently, the distribution of solution openings and fractures was used to define, in a qualitative sense, zones of high and low hydraulic conductivity for the digital model of the aquifer.

Computed values of transmissivity from field tests of the Upper Floridan aquifer generally range from about 2,000 to 1,300,000 ft^2/d (Hayes and others, 1983; Wagner and Allen, 1984). Wide variations in hydraulic conductivity are the result of variability in size and distribution of solution openings. Effective regional values of transmissivity usually range from about 2,000 to 300,000 ft^2/d (Hayes and others, 1983). Transmissivity is lowest near the updip limit of the Ocala Limestone, where the aquifer is relatively thin. Transmissivity generally increases to the south, where the aquifer thickens, and adjacent to major streams, where flowing water has accelerated the development of solution openings (Maslia and Hayes, 1988).

Lower Confining Unit

The lower confining unit in the lower ACF River Basin is the Lisbon Formation. The hard, well-cemented, and argillaceous nature of the limestone comprising the Lisbon Formation makes it a nearly impermeable base to the Upper Floridan aquifer (Hayes and others, 1983). Because of the relatively low hydraulic conductivity, compared with the Upper Floridan aquifer, wells yield only a few gallons per minute from the Lisbon Formation, although southeast of the Dougherty Plain, domestic supplies of water can be obtained (Hayes and others, 1983).

Recharge by vertical leakage to the Upper Floridan aquifer across the Lisbon Formation occurs in the northernmost part of the lower ACF River Basin at a rate of about 10 ft^3/s. Discharge from the Upper Floridan aquifer through the Lisbon Formation occurs in the southern part of the basin at a rate of about 5 ft^3/s, with no leakage in the central Dougherty Plain. In comparison, the total lateral flow component through the Upper Floridan aquifer is about 4,000 ft^3/s; thus, the Lisbon Formation is a nearly impermeable boundary to the Upper Floridan aquifer (Robert E. Faye and Gregory C. Mayer, U.S. Geological Survey, written commun., November 1990).

Ground-Water Levels

Ground-water levels in the study area exhibit fluctuations in response to seasonal recharge from infiltration of precipitation, extended periods of dry climatic conditions, discharge by pumpage and evapotranspira-

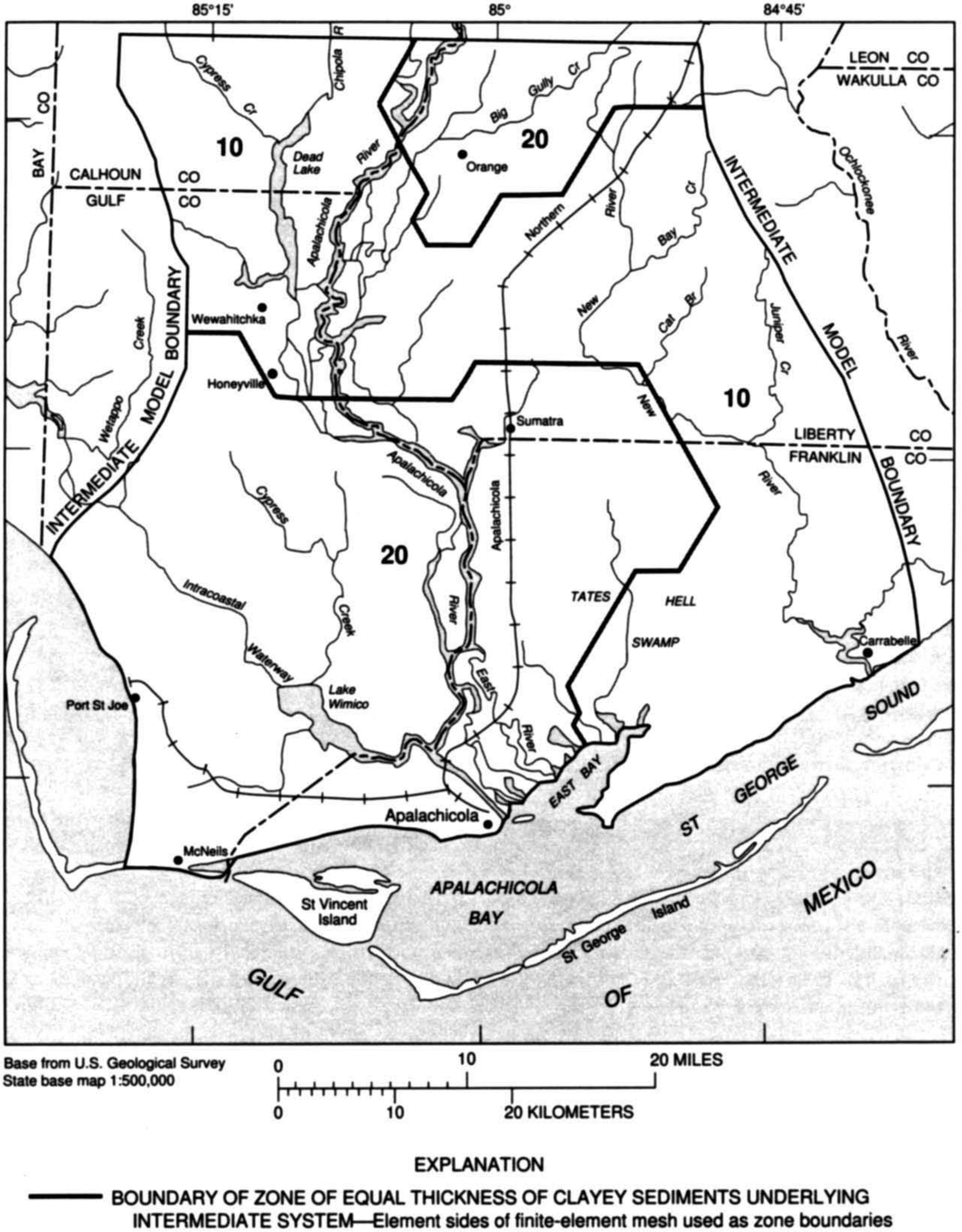

Figure 6. Zones of thickness of predominantly clayey sediments underlying the Intermediate system (from Torak and others,1996).

tion, and interaction with surface-water features. The natural pattern of high water-level altitude (or shallow depth to water with regard to land surface) in recharge areas and low water-level altitude in discharge areas, such as near streams, can be affected by heavy pumpage. Water levels generally range in altitude from about 340 ft in the Upper Floridan aquifer in northern parts of the basin, to slightly above sea level in the semiconfining unit on the flood plain along the coast. Neither response time nor magnitude of water-level changes in the semiconfining unit, Intermediate system, and Upper Floridan aquifer is predictable; it can vary areally within each hydrologic unit and can be either nearly instantaneous or very slow, and either large or barely perceptible.

Seasonal Fluctuations

The water level in the semiconfining unit overlying the Upper Floridan aquifer in the lower ACF River Basin usually is highest from January or February through April, declines during summer and fall, and is at a minimum during November through December or January (fig. 7). Beginning in December and continuing through January, water levels in wells generally rise quickly in response to recharge by infiltration of precipitation. During late spring and summer, however, water-level response to precipitation is subdued because the precipitation either replaces the soil-moisture deficit in the unsaturated zone or is lost to evapotranspiration (Hayes and others, 1983) or runoff. Also, summer precipitation generally is of the convective-storm type; thus, it is more intense and of shorter duration than precipitation associated with frontal passages during other seasons. During the measurement period of October 23–28, 1986, nearly all wells in the semiconfining unit were dry, indicating the severity of drought conditions.

Water-level fluctuations in the semiconfining unit overlying the Intermediate system in northwest Florida also are affected by seasonal variations in recharge from precipitation, and by seasonal changes in river stage, depending on the proximity to the Apalachicola River. Measurements of water table and river stage for water year 1980 by Leitman and others (1984) indicated that the water level in the semiconfining unit fluctuates about 1.5 to 5.5 ft annually in response to changes in river stage, with the smaller fluctuations occurring closer to Apalachicola Bay.

Ground-water levels in the Upper Floridan aquifer also fluctuate seasonally in response to precipitation, evapotranspiration, and pumping. Late winter and early spring recharge by infiltration of precipitation, coupled with low evapotranspiration and pumping rates, cause the water level in the Upper Floridan aquifer to reach a maximum during February through April (fig. 8). During the growing season, combined effects of ground-water pumpage for irrigation, evapotranspiration, and decreased recharge, compared with winter and spring conditions, cause the ground-water level to reach a minimum by late summer and through the fall. Seasonal water-level fluctuations range from about 2 ft in the eastern parts of the lower ACF River Basin in Georgia, to about 30 ft near Albany, Ga. (fig. 2). Near major centers of agricultural and industrial pumpage, seasonal water-level fluctuations probably exceed 30 ft and are amplified by drought conditions. Pumpage does not result in formation of distinct cones of depression (Hicks and others, 1987); rather, because of the relatively even distribution of pumped wells and magnitude of pumping rates, and the relatively high hydraulic conductivity, the potentiometric surface of the Upper Floridan aquifer is raised and lowered uniformly.

Very little water-level data exist to define seasonal fluctuations in wells tapping the Intermediate system. Water levels tend to decline toward the Apalachicola River (Jeffry R. Wagner, formerly of Northwest Florida Water Management District, Havana, Fla., written commun., 1988), and the river tends to regulate ground-water levels in its proximity. Water levels in the Intermediate system also are affected seasonally by water-level fluctuations in the overlying semiconfining unit. Because the underlying Upper Floridan aquifer is the primary source of ground water in the lower ACF River Basin, and population is low in areas of the basin where the Intermediate system is connected hydraulically to surface water, only a few wells tap the Intermediate system for domestic supply. Thus, large seasonal variations of water levels are not observed. The rural setting and small domestic supply needs preclude large seasonal variations in pumpage and water level from the Intermediate system.

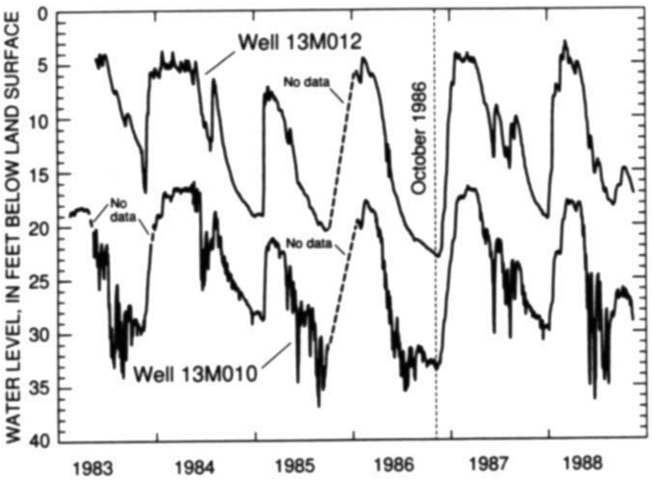

Figure 7. Water-level fluctuations in wells 13M010 and 13M012 in the semiconfining unit overlying the Upper Floridan aquifer, 1983–88 (from Torak and others, 1996). See plate 1 for location of wells.

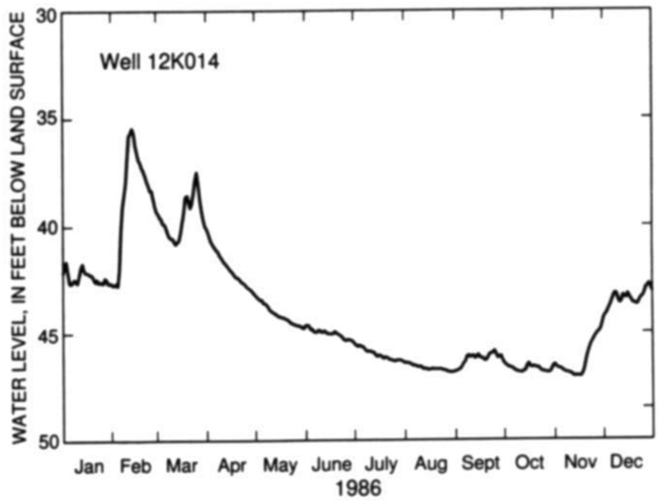

Figure 8. Water-level fluctuations in well 12K014 in the Upper Floridan aquifer, 1986 (from Torak and others, 1996). See plate 1 for location of well.

Long-Term Effects of Drought Conditions and Pumpage

Major water-bearing units in the lower ACF River Basin do not exhibit long-term declines in water levels from drought conditions or pumpage. During droughts of the early and late 1960's, 1980–81, and 1986–88, water levels in wells located in the Dougherty Plain of Georgia declined to record or near-record lows, but recovered to predrought levels with the return of normal precipitation (Hicks and others, 1987). Typical response of the Upper Floridan aquifer in Georgia to drought conditions is shown by water-level hydrographs of wells 13L003, 11K015, 12L028, and 12K014 (figs. 9–12).

Effects of drought conditions on water levels in wells located in the Upper Floridan aquifer in northwestern Florida are not as great as in Georgia, due to the rural setting, small population, and small (about 10 ft), seasonal, ground-water-level fluctuations in this area. Water levels in several wells located in Jackson and Gadsden Counties recovered sufficiently from dry conditions of 1980–81 to reach record-high water levels in early 1983 and 1984.

Predevelopment and recent (1985) potentiometric surfaces of the Upper Floridan aquifer (Wait, 1963; Hicks and others, 1987) show that 28 years of pumping at an average rate of about 66 Mgal/d from the Upper Floridan aquifer has not produced a long-term decline in the ground water level. Thus, recharge received from normal, annual rainfall is approximately equal to combined effects of natural and man induced discharge (Hicks and others, 1987, p. 22).

Limited water-level data indicate that pre drought conditions in the Intermediate system are quickly re-established with the return of normal precipitation. Because ground-water pumpage is small in the Intermediate system, no long-term effects of pumping have been observed.

Although most wells tapping the semiconfining unit above the Upper Floridan aquifer were dry in late October 1986, infiltration of normal precipitation during December and January quickly re-established pre-drought conditions (fig. 7). The Intermediate system behaves similarly, but is controlled by the stage of the Apalachicola River, seasonal recharge by infiltration of precipitation, and ground-water flow from adjacent upland areas (Leitman and others, 1984).

Effects of Surface-Water Features

Surface-water features have a variable effect on ground-water levels in the lower ACF River Basin. Despite the potential for hydraulic connection between the Upper Floridan aquifer and Flint River, sudden

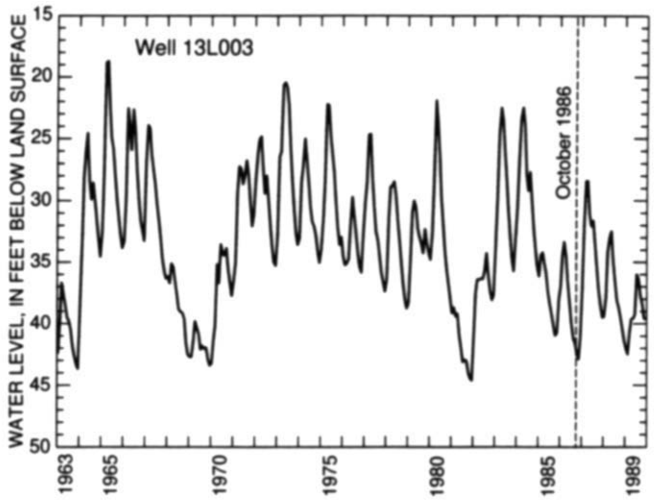

Figure 9. Water-level fluctuations in well 13L003 in the Upper Floridan aquifer, 1963–89 (from Torak and others, 1996). See plate 1 for location of well.

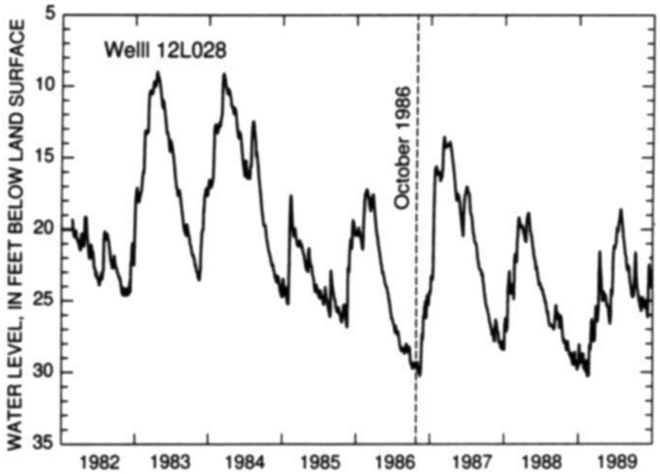

Figure 11. Water-level fluctuations in well 12L028 in the Upper Floridan aquifer, 1982–89 (from Torak and others, 1996). See plate 1 for location of well.

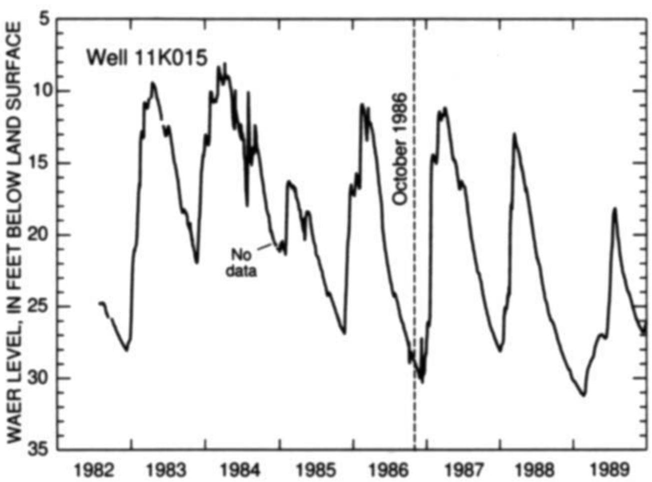

Figure 10. Water-level fluctuations in well 11K015 in the Upper Floridan aquifer, 1982–89 (from Torak and others, 1996). See plate 1 for location of well.

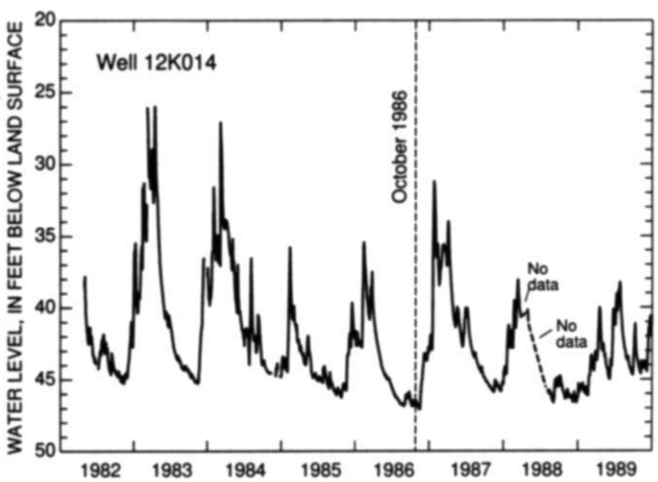

Figure 12. Water-level fluctuations in well 12K014 in the Upper Floridan aquifer, 1982–89 (from Torak and others, 1996). See plate 1 for location of well.

changes in river stage for short durations do not necessarily cause corresponding water-level changes in the aquifer. For example, during the period from February 21 to March 4, 1987, the stage of the Flint River at Albany, Ga., rose more than 12 ft in response to heavy rainfall in the northern part of the state. However, during this time, the water level in well 12K014, located less than 2 mi from the Flint River (pl. 1), increased by less than 2 ft (fig. 8).

Surface-water impounded behind dams affects ground-water levels in the lower ACF River Basin. At Lake Seminole, the pool elevation is maintained at an altitude of about 77 ft year round, causing water levels nearby in the adjacent aquifer and overlying semiconfining unit to be nearly constant. Lake Worth, impounded behind the Flint River Dam, located north of Albany, Ga., and Lake Blackshear, behind the Warwick Dam at the northern boundary of the study area (pl. 1), exhibit a similar influence on ground-water levels; although, the levels of these lakes fluctuate more than that of Lake Seminole. In addition to the effect of surface water, ground-water levels in the Upper Floridan aquifer near Lake Worth are influenced by regional flow from the north (Torak and others, 1993).

Downstream of Lake Seminole, the stage of the Apalachicola River influences ground-water levels in the flood plain. Observation wells across the flood plain near Blountstown and Sumatra, Fla. (pl. 1) indicate

that ground-water levels depend on river stage; however, water-level fluctuations in the river are damped in the flood plain by movement of water through the flood-plain soils (Leitman and others, 1984, p. A28).

Ground-Water Quality

Water in the Upper Floridan aquifer in the lower ACF River Basin is of good quality and generally does not contain constituent concentrations that exceed maximum contaminant levels established for drinking water by the Georgia Department of Natural Resources (1977) and the U.S. Environmental Protection Agency's (EPA) Primary or Secondary Drinking Water Regulations (1986a,b). In the northern part of the lower ACF River Basin, water in the Upper Floridan aquifer generally is a hard, calcium bicarbonate type, and is less mineralized than water in deeper aquifers (Hicks and others, 1981). In the central part of the basin, water in the Upper Floridan aquifer contains slightly higher specific conductance and concentrations of dissolved solids and phosphorus than in the northern part of the basin, indicating vertical movement of ground water through overlying, phosphate rich sediments (Mattraw and Elder, 1984). Water-quality information for water-bearing zones within the Intermediate system was not available; however, potential sources of water-quality degradation from agriculture or industry are low, and the water is assumed to be of good quality and suitable for most purposes.

Water-quality samples from the Upper Floridan aquifer and Flint River at Newton were collected as part of a previous investigation by Hicks and others (1987). The analysis by Hicks and others (1987, p. 33–36) indicated that the general quality of water in the Upper Floridan aquifer is suitable for most purposes, although trace concentrations of agricultural pesticides and industrial degreasers were detected in some wells. These compounds probably entered the aquifer with vertical leakage (recharge) of ground water from the overlying semiconfining unit of the undifferentiated overburden. However, as stated by Hicks and others (1987, p. 35), the samples indicated a one time concentration of these constituents in the aquifer at specific locations, and flushing (transport) or dilution at these locations precluded detection at a later time.

Surface Water

Hydrologic factors affecting the surface-water resources also affect its interaction with ground water by regulating flow across streambeds and play an essential role in the evaluation of stream-aquifer relations. The drainage network established by streams provides evidence of water-resource availability; both the magnitude and duration of streamflow indicate its availability as a source of water to recharge the aquifer by seepage or leakage; and control structures show man's attempt to harness the resource for various purposes. These 3 elements of the surface-water system are discussed as they pertain to stream-aquifer relations in the lower ACF River Basin.

Drainage

The Chattahoochee River enters the central part of the study area east of Dothan, Ala. (pl. 1), and drains about 1,800 mi^2 of Coastal Plain sediments. The river is deeply incised within its flood plain and cuts into the underlying limestone aquifer (Hayes and others, 1983). There are no large tributaries to the Chattahoochee River within the study area; only small streams and creeks, such as Sawhatchee Creek, that drain the undifferentiated overburden to the limestone. The Chattahoochee River flows roughly 50 mi south-southeastward from the study-area boundary to Lake Seminole, a manmade impoundment formed at the Georgia-Florida border at the confluence of the Chattahoochee and Flint Rivers behind Jim Woodruff Lock and Dam (pl. 1).

The Flint River enters the extreme northern part of the study area about 7 mi north of Lake Blackshear (pl. 1) and drains about 6,000 mi^2 within the Coastal Plain. Major tributaries originate west of the River within the Coastal Plain and include Cooleewahee, Ichawaynochaway, Kinchafoonee, and Spring Creeks. Only minor tributaries exist east of the Flint River from the Solution Escarpment, which creates a ground-water and surface-water divide and forms the eastern basin boundary. Spring Creek rises north of Colquitt,

Ga., near the Calhoun-Early County line (pl. 1) and flows south into Lake Seminole, about 3 mi northeast of the confluence of the Flint and Chattahoochee Rivers (Hayes and others, 1983).

The Apalachicola River drains 2,400 mi^2 of Coastal Plain sediments as it flows 106 mi from Lake Seminole to Apalachicola Bay in the Gulf of Mexico (pl. 1). The major tributary to the Apalachicola River is the Chipola River, which drains exactly half of the total area drained by the Apalachicola River (Mattraw and Elder, 1984). Two distributaries, the Chipola Cutoff and Brickyard Cutoff, convey water from the Apalachicola River but subsequently return flow to the river downstream of the diversions (fig. 3). The Chipola Cutoff conveys water from the Apalachicola River to the Chipola River near Wewahitchka, Fla. These waters rejoin the main stem of the Apalachicola River about 13 mi downstream (Mattraw and Elder, 1984). The Brickyard Cutoff conveys water from the Apalachicola River to the Brothers River near Sumatra, Fla. The Brothers River rejoins the Apalachicola about 8 mi south of Brickyard Cutoff. About 6 mi further downstream, the Apalachicola River joins the Jackson River and flows southeast into Apalachicola Bay.

The Apalachicola River Basin was divided into 3 zones by Leitman and others (1984) according to river-channel morphology, drainage characteristics, and physiography. The following drainage description is summarized from their report. The upper-river corridor is defined as the region from Chattahoochee to Blountstown, Fla. (pl. 1). In this region, the river cuts through sediments of Miocene age. The width of the flood plain varies from 1 to 2 mi, and the channel is characterized by long, straight reaches and wide, gentle bends. The middle zone of the river from Blountstown to Wewahitchka, Fla., lies in Holocene and Pleistocene deposits and has a wider flood plain (2 to 3 mi) than the upper-river reach. The river channel meanders in large loops through this region and has many small, tight bends to the south (fig. 3). The lower zone of the river from Wewahitchka to Apalachicola, Fla., lies entirely within the Gulf Coastal Lowlands physiographic district and flows over Holocene and Pleistocene deposits. The flood plain ranges in width from 2.5 to 4.5 mi, and the channel is characterized by long, straight reaches having a few small bends.

Streamflow

Streamflow in the lower ACF River Basin is affected by natural and man-induced factors. Descriptions of streamflow variation and stream stage and discharge hydrographs for streams in the lower ACF River Basin are given by Hayes and others (1983), and Leitman and others (1984). In general, high streamflows can be used to indicate direct runoff resulting from climatic factors, watershed physiography, and vegetation, whereas low streamflows tend to indicate base flow or the ground-water component of streamflow. Streamflow varies seasonally; low flows usually occur from September to November, and high flows occur from January to April each year. Flood conditions vary greatly from year to year and might not follow seasonal trends in any given year (Leitman and others, 1984). Streamflow is decreased by ground-water withdrawals, primarily in parts of the basin located in Alabama, Georgia, and in northernmost counties of Florida, by intercepting regional flow in aquifers that, in the absence of pumpage, would discharge this water to streams (Torak and others, 1996). The relations of ground-water level, precipitation, and streamflow in the northern part of the lower ACF River Basin have been described by Hayes and others (1983). Additional discussion of these relations can be found in this reference (see p. 16–18 of Hayes and others, 1983).

The upper-river corridor of the Apalachicola River, from Chattahoochee to Blountstown, Fla., exhibits a larger range in river stage fluctuations than the lower river (fig. 13) partly because of differences in basin physiography and hydraulic properties of sediments drained by the upper and lower river. Natural-riverbank levees either prevent flood-plain water from entering the river or prevent river water from entering the flood plain. The river receives ground water from the water table in the flood plain at low stages and either loses water or does not contribute to the water table during high stages. Tidal fluctuations in the lower river vary greatly with river stage and tidal cycles, but generally range from about 1.5 to 2.3 ft in amplitude and extend about 20 to 25 mi upstream from the mouth of the Apalachicola River (U.S. Army Corps of Engineers and others, 1984).

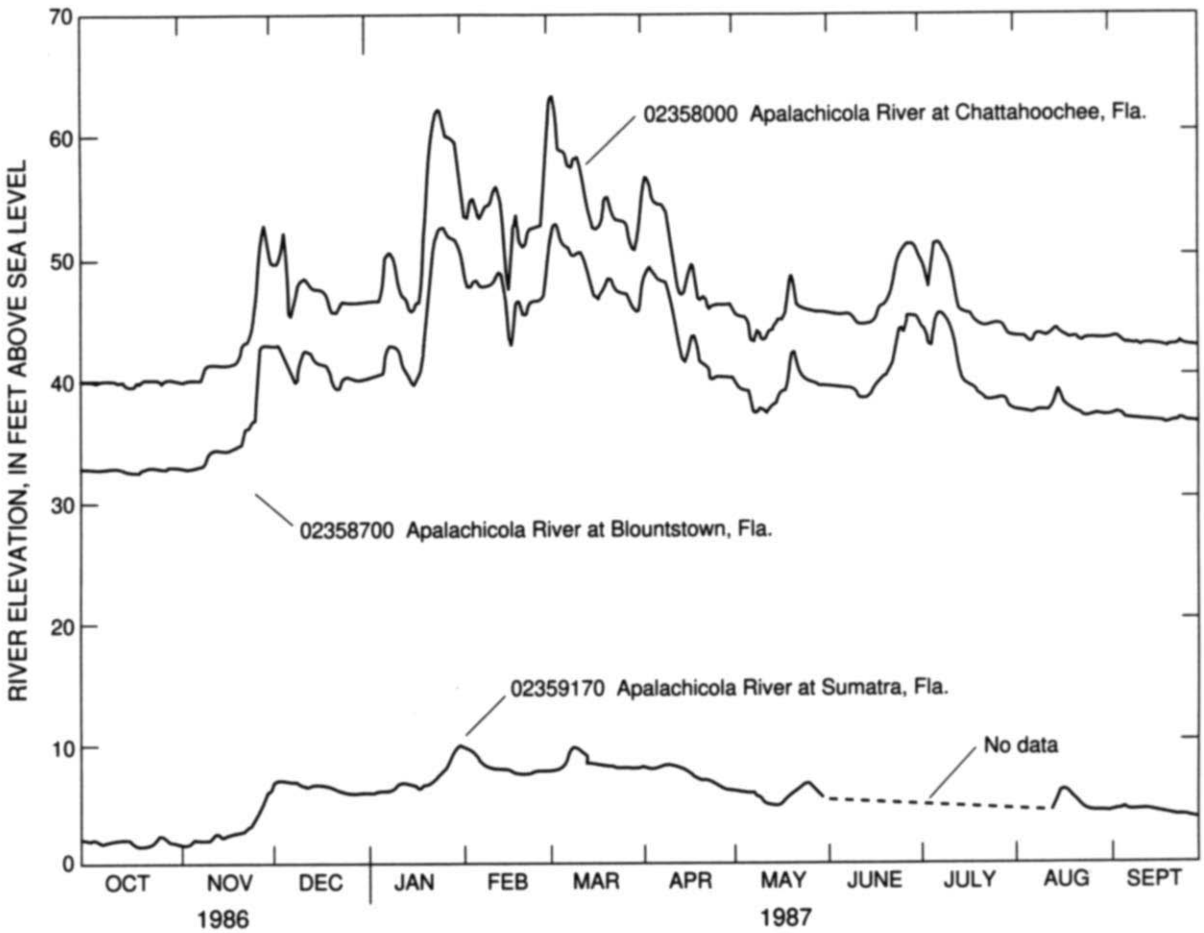

Figure 13. River stage for three gaging stations on the Apalachicola River, October 1986 to September 1987 (from Torak and others, 1996). See plate 1 for location of gaging stations.

Of particular interest to this study is the ground-water component of streamflow, or base flow. River stage and streamflow hydrographs (figs. 13–15) at continuous- and partial-record measurement stations indicate that seasonal and low flow conditions existed in the lower ACF River Basin. Some of the upper reaches of small streams were dry, further attesting to the severity of the October 1986 drought. The October 1986 stream discharges were near or below historic lows and, therefore, were used as an estimate of base flow.

Dams and Navigational Improvements

Three dams and their associated surface water impoundments reside in the lower ACF River Basin. The Warwick Dam (pl. 1) impounds Lake Blackshear and is the most upstream control structure on the Flint River. It is located about 33 mi upstream from Albany. About 2 mi north of Albany is the Flint River Dam (pl. 1), which impounds several lakes at that location. The Flint River Dam actually consists of two dams: one on the Flint River and one on Muckafoonee Creek. The impoundments behind these dams are connected by an excavated channel (U.S. Army Corps of Engineers and others, 1984). Both dams are run-of-the-river structures used for hydropower generation and do not affect downstream flows appreciably.

Jim Woodruff Lock and Dam (pl. 1) is the southernmost impoundment structure in the lower ACF River Basin. It is located about 1 mi downstream of the confluence of the Chattahoochee and Flint Rivers at the Georgia-Florida State line and impounds Lake Seminole, a 37,600-acre reservoir which provides headwater to the Apalachicola River. Construction of the dam by the U.S. Army Corps of Engineers began in 1950, and filling of the reservoir to its normal pool altitude of 77 ft occurred in stages from May 1954 to February

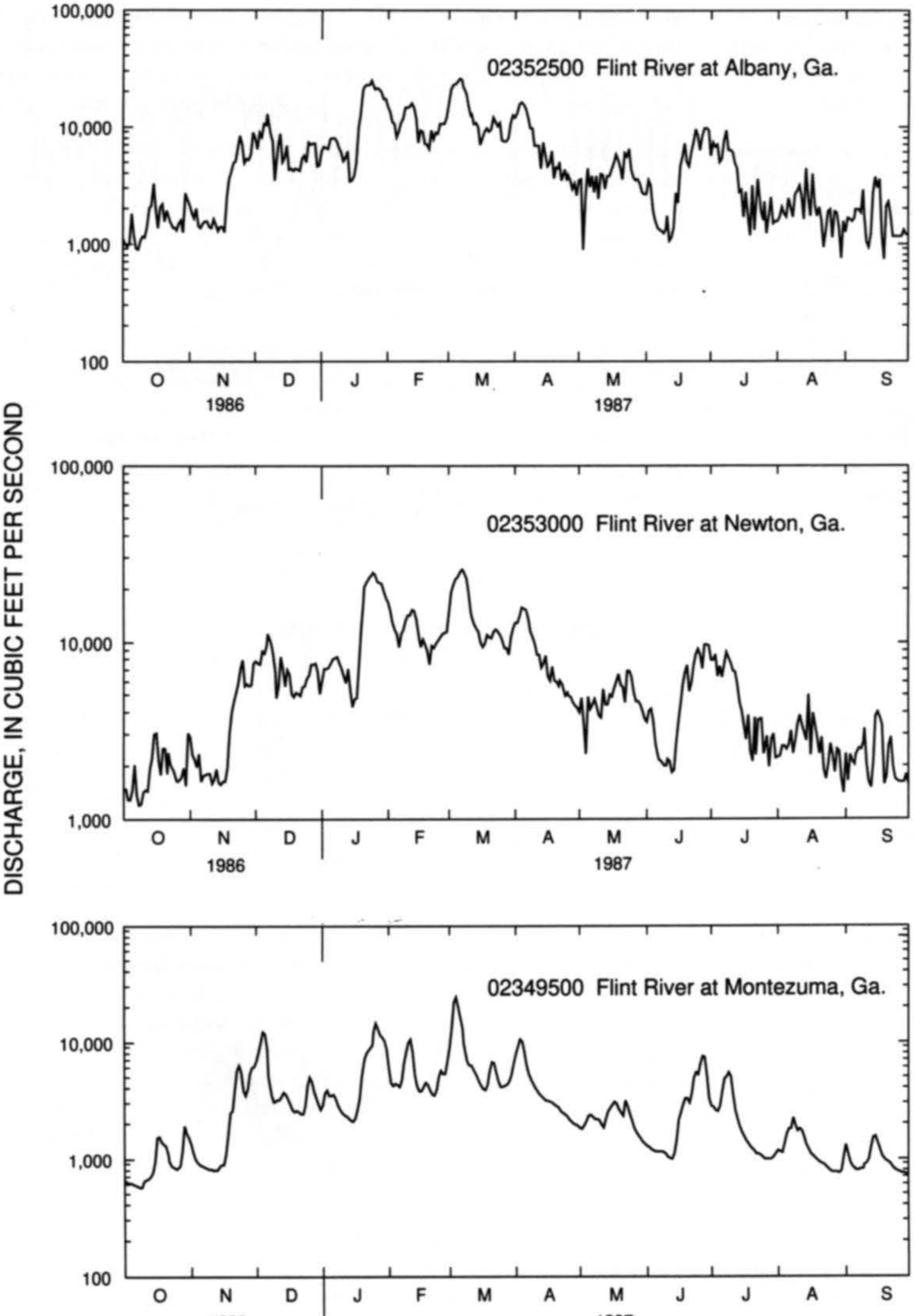

Figure 14. Streamflow for three gaging stations on the Flint River, October 1986 to September 1987 (from Torak and others, 1996). See plate 1 for location of gaging stations.

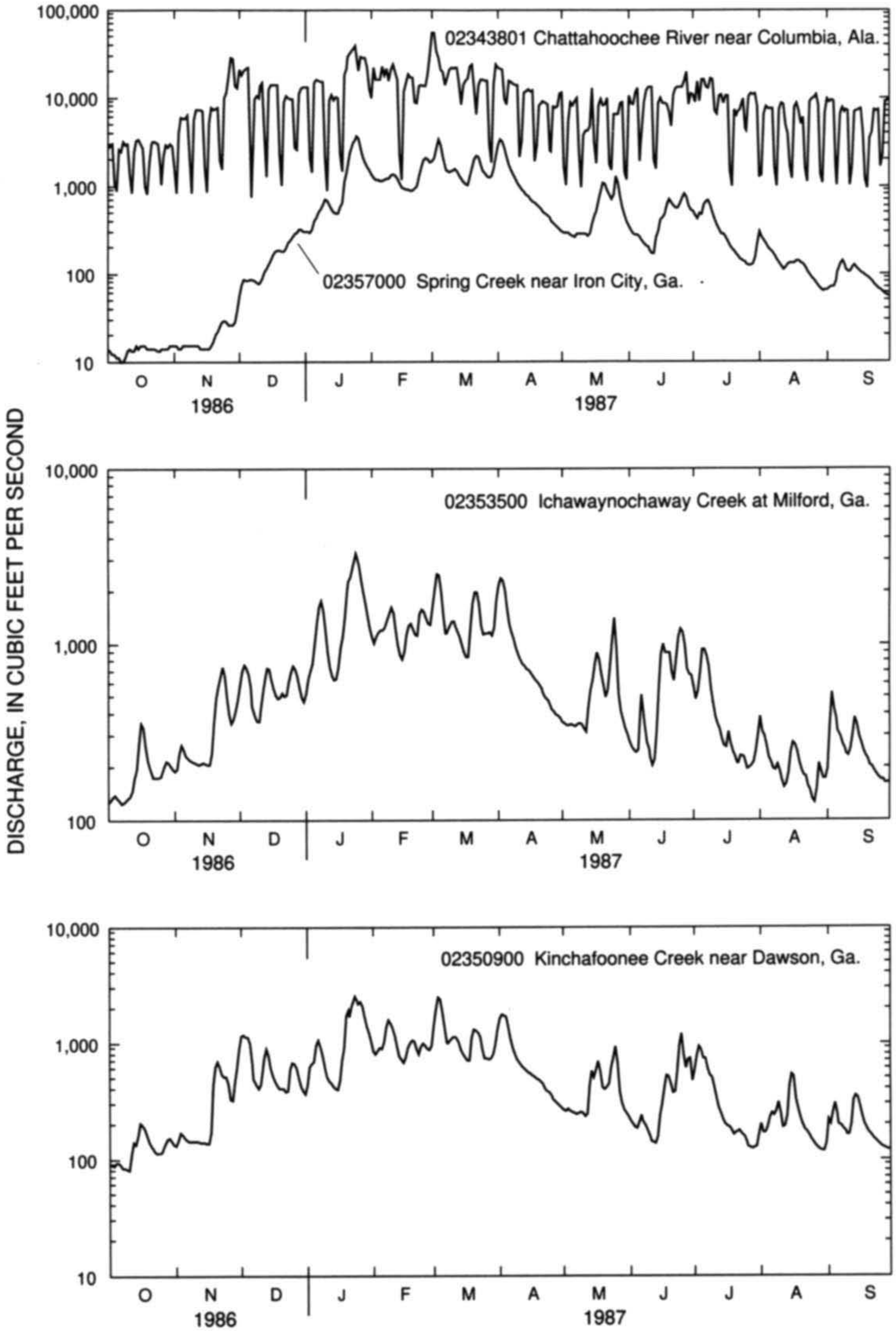

Figure 15. Streamflow for gaging stations on the Chattahoochee River and on Ichawaynochaway, Kinchafoonee, and Spring Creeks, October 1986 to September 1987 (from Torak and others, 1996). See plate 1 for location of gaging stations.

1957. The dam was constructed primarily to aid navigation of barge traffic on the Apalachicola, Chattahoochee, and Flint Rivers, with hydropower generation as a secondary benefit. Despite its size, Lake Seminole is essentially a run of the river impoundment having less than 67,000 ac ft of useful storage (U.S. Army Corps of Engineers and others, 1984).

Navigational improvements such as dredging, cutoffs, and groins (dikes partially extending into the stream channel perpendicular to banks) have been made in the principal rivers of the lower ACF River Basin by the U.S. Army Corps of Engineers. The Corps is authorized to maintain channels 100-ft wide and 3- and 9-ft deep at specific locations in these rivers. Upstream of the Flint River Dam to Montezuma, Ga. (north of Lake Blackshear and the study-area boundary; pl. 1), the channel is maintained suitable for navigation of light draft vessels. From Albany to Bainbridge, Ga., the channel is maintained at a 3-ft depth; from Bainbridge, Ga., to Jim Woodruff Lock and Dam and in the Apalachicola River, a 9-ft-deep channel is maintained. A 9-ft-deep channel also is maintained on the Chattahoochee River from Columbus, Ga., to the Dam. Dredging for the 9-ft depth began in 1956 in preparation for completion of Jim Woodruff Dam (Leitman and others, 1984). Since 1956, 7 cutoffs were made at meanders (bends) in the Apalachicola River to straighten the channel for barge navigation. One cutoff is located about 1 mi upstream of the confluence of the Chipola and Apalachicola Rivers (pl. 1). Groins were placed mostly in the upper part of the Apalachicola River to create channel scour and improve navigation. Twenty nine sets of groins, made of wooden pilings or stone, were installed in the river. Usually, each set contains 4 groins, but as few as 2 or as many as 8 were installed in some locations (Leitman and others, 1984).

EVALUATION OF GROUND-WATER RESOURCES

Evaluation of ground-water resources in the lower ACF River Basin demands an equal evaluation of stream-aquifer relations. Interactions among hydrologic factors in the surface- and ground-water-flow systems tend to merge the physical cause-and-effect relations associated with these flow systems such that they can be regarded as a single-resource entity. Surface- and ground-water-flow systems are connected hydraulically by a streambed or lakebed; hence, evaluation of ground-water (and surface-water) resources requires quantification of leakage across this hydrologic boundary, and evaluation of the hydraulic properties and relative water levels of both systems. Changes to these factors, either by natural or manmade processes, affect water-resource availability and stream aquifer relations.

Ground-water resources in the lower ACF River Basin are evaluated in this study by determining effects of the following hydrologic characteristics on the ground-water-flow system and its interaction with surface water: ground-water levels that control lateral- and vertical-flow-boundary conditions; stream stage; and variations in ground-water pumpage from the October 1986 rates. Complex relations of these characteristics in space and in time necessitated that computer simulation be used to evaluate flow-system response to changes in hydrologic conditions. Simulation provided a means to quantify changes in ground-water level and stream-aquifer flow (flow rate of water across streambeds or lakebeds; principally, the ground-water component of streamflow) caused by simultaneous changes in these conditions. Water budgets that were developed from simulation results provided estimates of regional ground-water flow across basin and state boundaries, and enabled the effects of changed hydrologic conditions on resource availability to be quantified.

In a previous study of the lower ACF River Basin (Torak and others, 1996), digital models of two-dimensional ground-water flow in the Upper Floridan aquifer and Intermediate system, the hydrologic units in contact with surface-water features in the basin, were calibrated to steady-state, low-flow conditions of October 1986. These simulations serve as the basis for simulations of steady-state and nonsteady-state (or transient) conditions that were performed in this study to evaluate ground-water resources. Due to the importance of this previous work and its relevance to the evaluation, some details of the steady-state simulations are repeated in following sections of this report so that a complete hydrologic analysis of ground-water resources is documented here.

Conceptualization of the Flow System

Conceptualization of the surface- and ground-water-flow system in the lower ACF River Basin was based on interpretation of available hydrologic data given in preceding sections. This conceptualization was a prelude to forming a working hypothesis, or a conceptual model, of the stream-aquifer system, which was tested by using simulation.

Equilibrium of the flow system was reached in October 1986, when temporal changes to ground-water levels in response to the many and complex hydrologic boundaries seemed to cease. The cessation of temporal changes in ground-water levels was interpreted as a steady-state condition for the ground-water-flow system. In addition, water levels in wells completed in the Upper Floridan aquifer and in water-bearing units of the Intermediate system and overlying semiconfining units were either at or near seasonal or record lows and were maintained at these levels for a period of time necessary for the flow system to equilibrate, or reach steady-state conditions.

Recharge to the flow system by infiltration of precipitation was negligible due to extremely dry climatic conditions that prevailed in the lower ACF River Basin during 1986. Vertical leakage from clayey sediments in the semiconfining units provided one of the few sources of water to the aquifer for October 1986; other aquifer recharge included lateral flow across surface-water divides and vertical leakage from surface water. Ground-water recharge was balanced identically by discharge to surface water and to wells, and by discharge across lateral- and vertical-flow boundaries.

For ease of conceptualization, the lower ACF River Basin is separated into 3 parts (fig. 16) according to the hydrologic units that contact surface-water features and contribute to stream-aquifer relations. Descriptions of these units and of ground- and surface-water flow in each part provide a framework for simulations to evaluate ground-water resources and stream-aquifer relations. In the northern part of the basin, surface-water features are in hydraulic connection with the overlying semiconfining unit and the Upper Floridan aquifer (fig. 17). In this part of the basin, the Upper Floridan aquifer consists primarily of the Ocala Limestone and, where present, the Clinchfield Sand. The northern boundary of the study area is defined by the saturated, updip limit of the aquifer in the outcrop area. Surface-water features (streams, reservoirs, and lakes) are in hydraulic connection with the Upper Floridan aquifer and alluvium; however, only the aquifer contributes water to streamflow as most of the water-bearing zones in the alluvium were dry during October 1986. The aquifer is semiconfined above by undifferentiated overburden and terrace and undifferentiated (alluvial) deposits, and is confined effectively below by the Lisbon Formation, which creates a lower-confining unit in Georgia and a sub-Floridan confining unit in Florida (fig. 4). Because of similar geologic and stratigraphic relations in the Alabama part of the study area as in Georgia, particularly near outcrop areas immediately adjacent to the Chattahoochee River, the Lisbon Formation is assumed to be hydraulically disconnected from the stream-aquifer system in Alabama as well as in Georgia. In addition, any hydraulic interaction of the Lisbon Formation in Alabama with the overlying Upper Floridan aquifer is assumed to be negligible.

Within the overburden, water-bearing zones of limited areal extent supply small amounts of water to streams and are the primary recharge mechanism to the Upper Floridan aquifer by vertical leakage. The low hydraulic conductivity of the clayey sediments inhibits lateral flow of water to streams and aquifer recharge by vertical leakage, particularly in response to pumpage in the aquifer. Variations in thickness and content of sand and clay in the overburden (Hayes and others, 1983) create areas of locally high and low leakage rates across the upper-vertical boundary of the aquifer. These variations typically occur in small areas of some sinkholes, swallowholes, and closed depressions, which are evidence of Karst processes at work in the underlying Upper Floridan aquifer. Head in the clayey lower half of the overburden was nearly constant for October 1986 conditions.

The Upper Floridan aquifer is well drained in the northern part of the lower ACF River Basin by the Chattahoochee and Flint Rivers and by numerous streams. In some areas the rivers and streams deeply incise the undifferentiated overburden and maintain direct hydraulic connection with the aquifer (fig. 17). In other

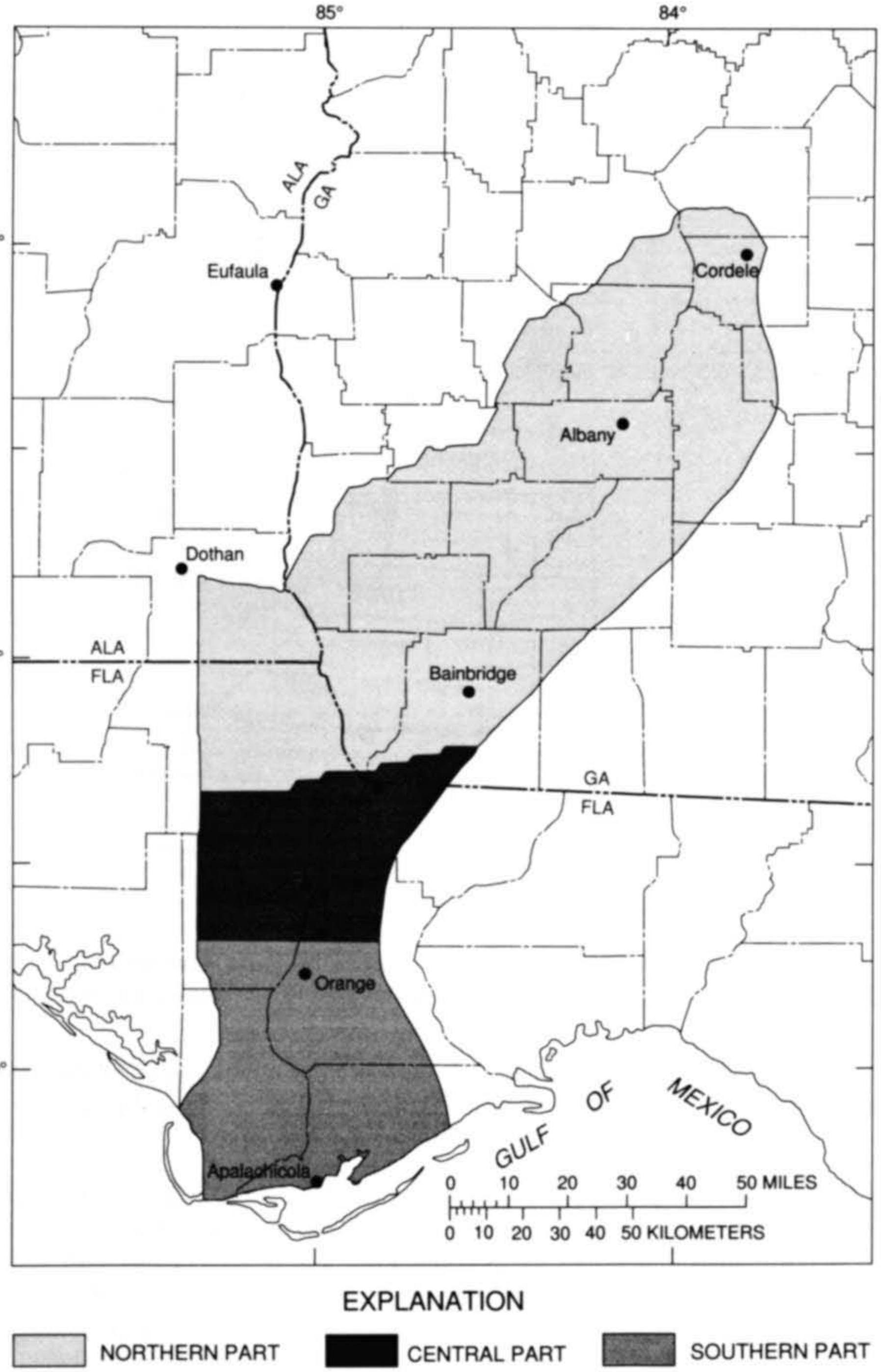

Figure 16. Division of study area into northern, central, and southern parts for conceptualization of flow system (from Torak and others, 1996).

areas, the hydraulic connection is indirect, as surface-water features are separated from the aquifer by overburden or sediments of low hydraulic conductivity. Surface-water features that indirectly connect to the Upper Floridan aquifer have only a minor influence on shaping the potentiometric surface of the aquifer.

In the northern part of the lower ACF River Basin, ground-water flow in the Upper Floridan aquifer is influenced by regional inflow from outcrop areas and across basin boundaries to the east and west, by pumpage, and by discharge to rivers and major streams. Ground water also flows south from this part of the basin

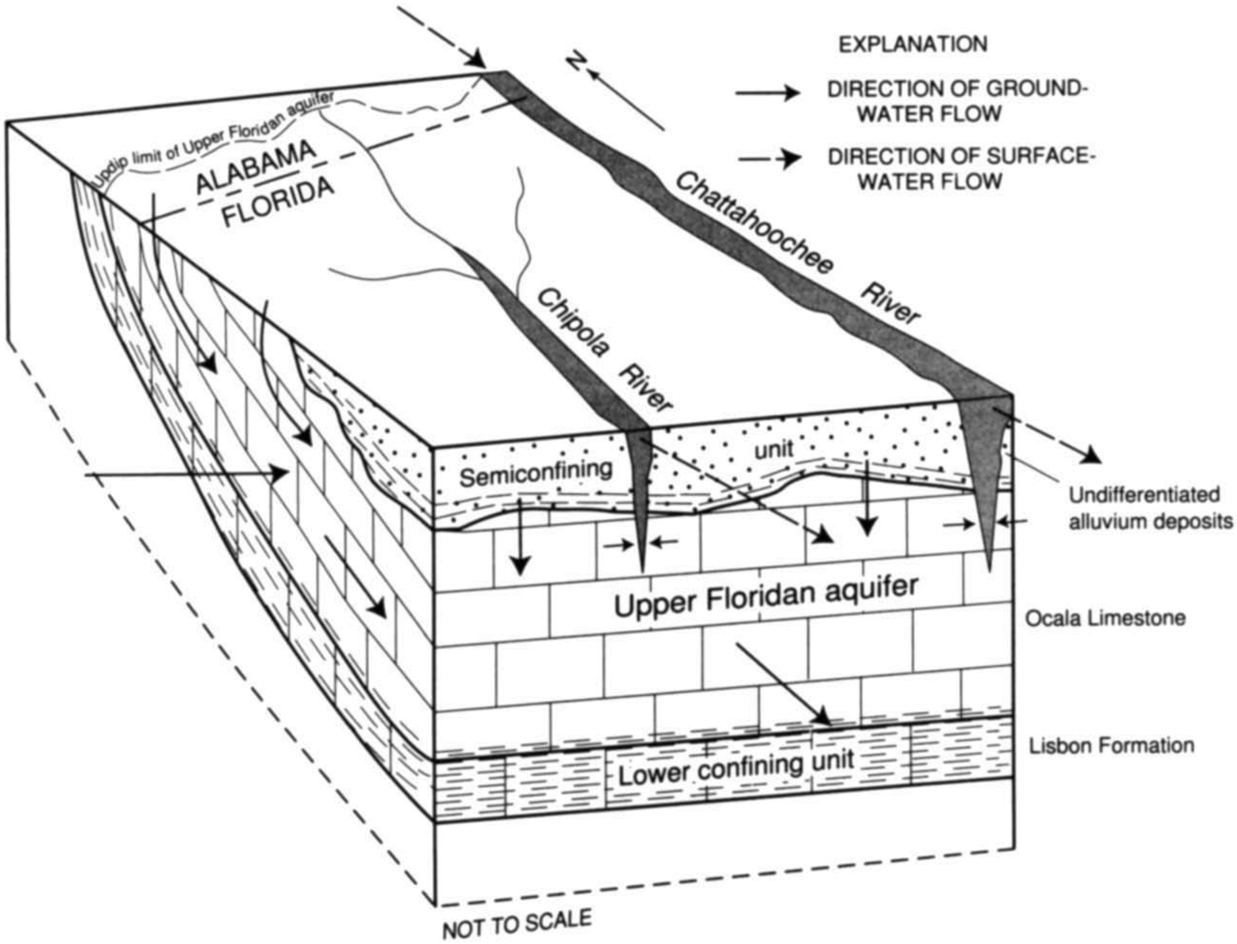

Figure 17. Idealized block diagram of the northern part of the lower Apalachicola–Chattahoochee–Flint River Basin and conceptualization of ground-water flow (from Torak and others, 1996).

to the central part. Inflow across the eastern boundary occurs from upland areas of the Solution Escarpment. Regional inflow across the western boundary is small and discharges to the drainage network of the Chattahoochee River.

Changes in ground-water-pumping rates can change the direction and magnitude of regional flow from those conceptualized for the northern part of the lower ACF River Basin. Increased pumpage can induce regional inflow from outcrop areas and across basin boundaries, and in some areas shift ground-water-flow divides outward from present positions. Decreased pumpage can have an opposite effect; reduce regional inflow to the basin and shift ground-water divides inward toward existing or former pumpage centers.

In the central part of the lower ACF River Basin, variations in lithology and hydraulic properties of the Upper Floridan aquifer and in the pattern of surface-water drainage create distinct flow regimes for the stream-aquifer system to the east and west of the Apalachicola River (fig. 18). The Upper Floridan aquifer consists of the following geologic units, in descending order, the Tampa and Suwannee Limestones, Marianna Formation, and Ocala Limestone (fig. 4). Surface-water features are in hydraulic connection primarily with the Upper Floridan aquifer. A small amount of ground water contributes to surface water from zones in the overlying semiconfining unit and Intermediate system, but were considered negligible for the drought conditions of October 1986 and for this conceptualization.

The distinction in flow regimes in the Upper Floridan aquifer east and west of the Apalachicola River focuses around whether to consider the Tampa Limestone as part of the aquifer in contact with surface water

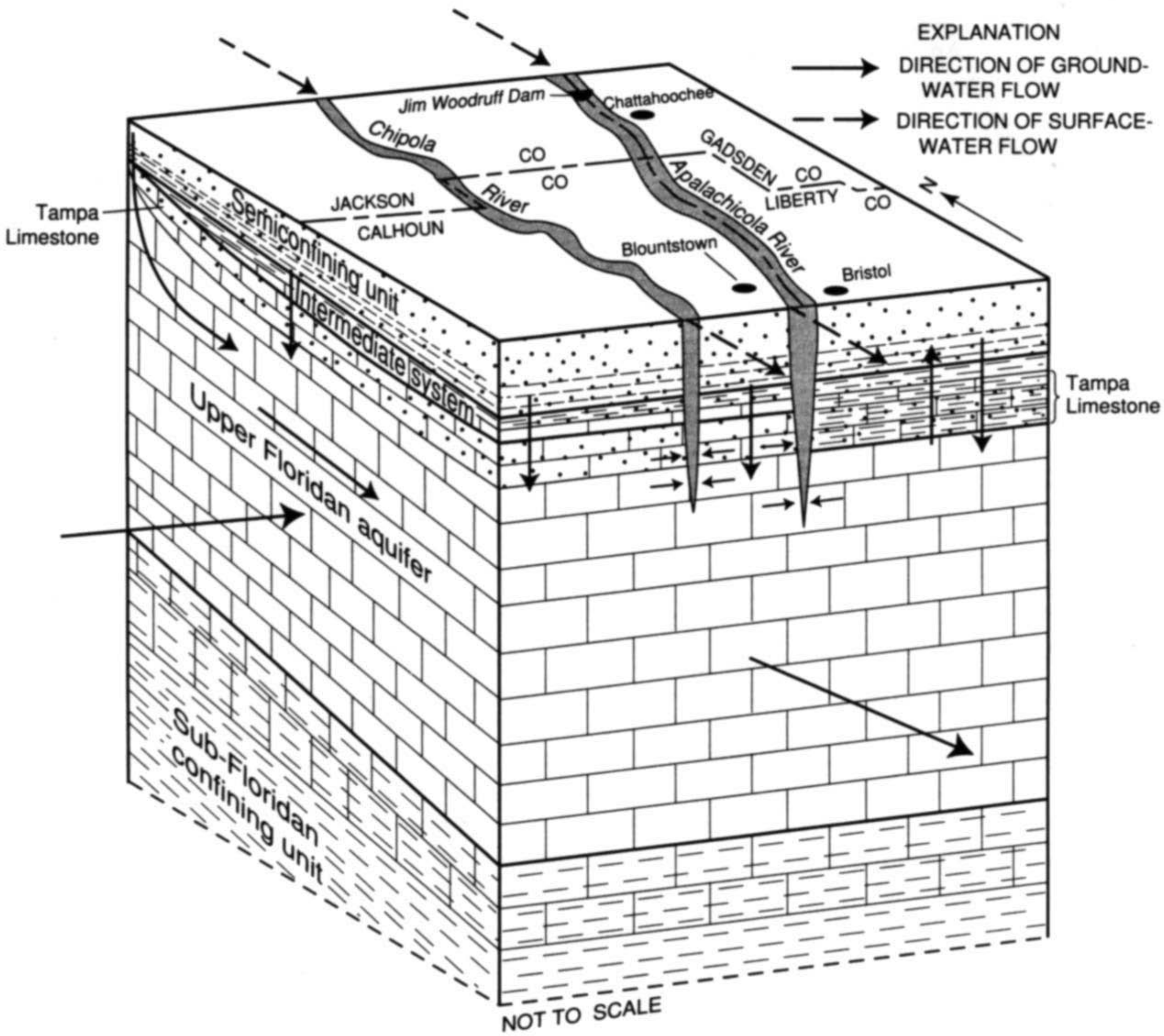

Figure 18. Idealized block diagram of the central part of the lower Apalachicola–Chattahoochee–Flint River Basin and conceptualization of ground-water flow (from Torak and others, 1996).

or as part of the overlying semiconfining unit. The Tampa Limestone is not in hydraulic connection with surface water east of the Apalachicola River, as the river has incised below the base of this unit, exposing the Tampa Limestone in bluffs along the eastern boundary of the flood plain. In addition, there is a lack of well developed surface-water drainage in the Tampa Limestone east of the Apalachicola River. Compared with the deeper limestones of the aquifer, the fine-grained and clayey lithology of the Tampa Limestone provides the potential to support higher ground-water levels; potentiometric surfaces prepared in a previous investigation show that east of the Apalachicola River, water levels in the Tampa Limestone are 70 to 90 ft higher than water levels in deeper units (Jeffry R. Wagner, formerly with the Northwest Florida Water Management District, Havana, Fla., written commun., 1988). Therefore, the combination of poor surface-water drainage and low-water-transmitting ability enables the Tampa Limestone east of the Apalachicola River to function as a semiconfining unit, providing a source of water to the deeper units of the Upper Floridan aquifer, and being disconnected, hydrologically, from stream-aquifer relations.

West of the Apalachicola River, the Tampa Limestone and deeper units are cut by the well-developed-drainage network of the Chipola and Apalachicola Rivers. The sandy lithology of the Tampa Limestone west of the Apalachicola River, in comparison with more clayey lithology to the east, enables it to be drained easily by surface water, creating nearly uniform ground-water levels in all units of the Upper Floridan aquifer.

Therefore, west of the Apalachicola River, all limestone units of the Upper Floridan aquifer are in hydraulic connection with surface-water features, and the aquifer is semiconfined above by clayey sediments in the overlying semiconfining unit and Intermediate system. On both sides of the river, the Upper Floridan aquifer is confined effectively from below by the sub-Floridan confining unit.

Regional ground-water flow in the Upper Floridan aquifer in the central part of the lower ACF River Basin follows the same general directions as that described for the northern part. Ground-water levels in wells indicate that the Upper Floridan aquifer receives inflow across the eastern- and western-basin boundaries and from regional flow out of the northern part. Ground water discharges from the Upper Floridan aquifer to the Chipola and Apalachicola Rivers, and flows regionally across the southern boundary of the central part of the basin.

In the northern and central parts of the lower ACF River Basin, ground water discharges to springs emanating from the Upper Floridan aquifer. Springs are located either in streambeds (in-channel springs) or adjacent to streams (off-channel springs), and can be part of streamflow after flowing a short distance over land, such as Radium Springs near the Flint River in Georgia (pl. 1). In general, off-channel springs are located in Gadsden, Jackson, and Liberty Counties, Fla. Off-channel springs that are situated far from streams might not discharge directly to surface water and, thus, might only cause local changes to regional ground-water movement. In-channel springs contribute to streamflow gain along a reach and might be indistinguishable from other in-channel sources of water, such as ground-water leakage across the streambed bottom.

In the southern part of the lower ACF River Basin, the stream aquifer system consists of water-bearing zones in the overlying semiconfining unit and Intermediate system. The underlying Upper Floridan aquifer is too deep stratigraphically to be in hydraulic connection with surface-water features in this part of the basin (fig. 19); consequently, it is not represented in simulations as such. Water-bearing zones in the overlying semiconfining unit are of small areal extent and contribute negligibly to flow of the Apalachicola River. The hydraulic connection between water bearing units in the Intermediate system and surface-water features is indirect, as ground water discharges from these units to the river through sediments having low hydraulic conductivity.

Recharge to and discharge from the Intermediate system in the southern part of the lower ACF River Basin occur as vertical leakage across the boundaries of the aquifer with overlying and underlying semiconfining units (fig. 19). To the north, vertical leakage from source layers in the overlying semiconfining unit provides recharge to the Intermediate system. To the south, recharge to the Intermediate system is from below, as the water level in the underlying Upper Floridan aquifer is slightly higher than the water level in this unit (Jeffry R. Wagner, formerly of Northwest Florida Water Management District, Havana, Fla., written commun., 1988). These patterns of vertical leakage provide sources of ground water for the Intermediate system that discharge to surface-water features in the southern part of the basin.

Mathematical Model

The mathematical model used to simulate ground-water flow with stream-aquifer relations in the lower ACF River Basin consists of partial-differential equations that are assumed to describe the physics of fluid flow in porous media and appropriate boundary conditions. Variants of the governing equation and boundary conditions given in Cooley (1992) are presented as they apply to flow in the Upper Floridan aquifer and water-bearing units of the Intermediate system.

Governing Equation

Ground-water flow in the Upper Floridan aquifer and water-bearing units of the Intermediate system within boundaries of any discontinuities in transmissivity or within external boundaries is assumed to be governed by the following two-dimensional, nonsteady-state flow equation

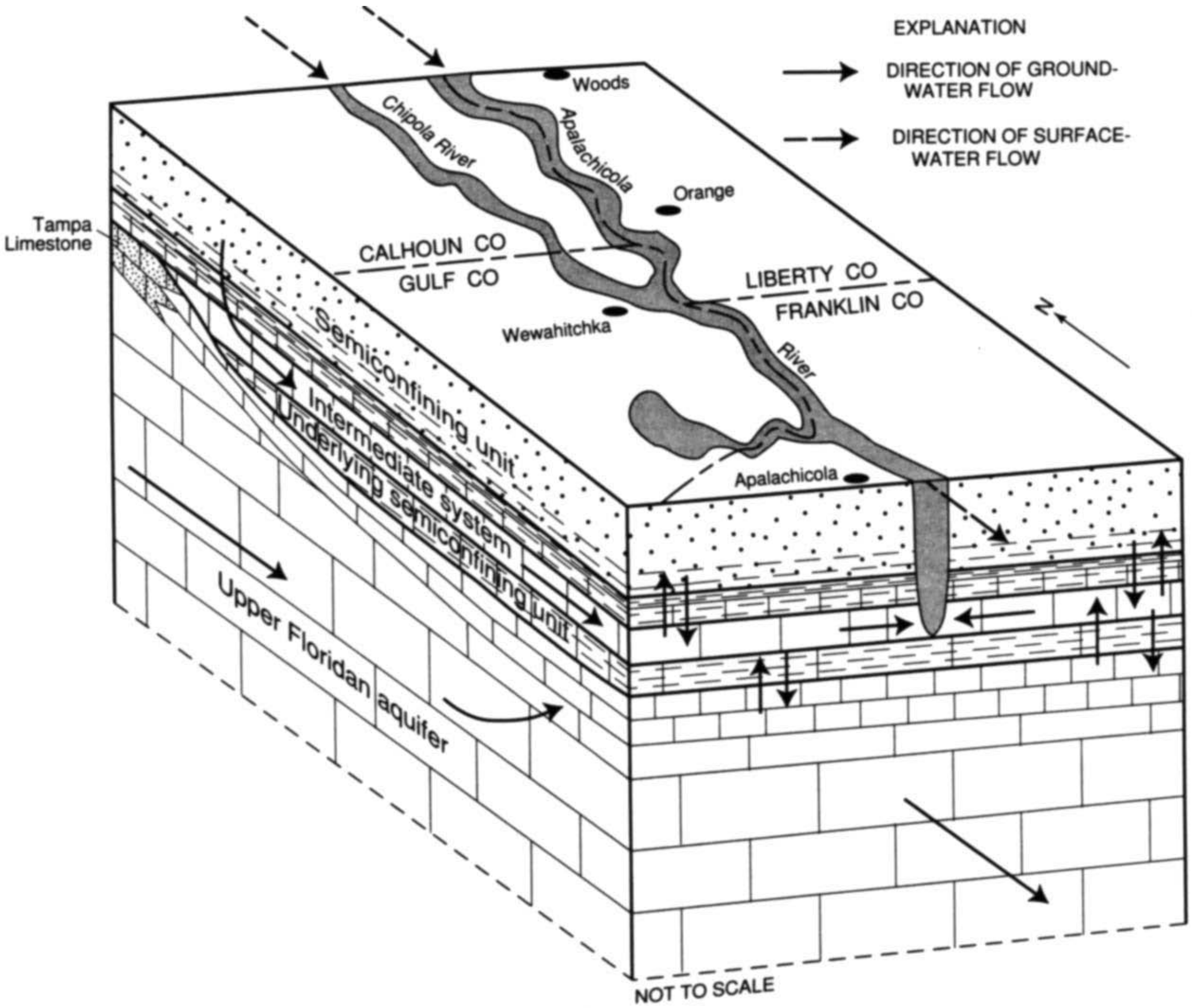

Figure 19. Idealized block diagram of the southern part of the lower Apalachicola–Chattahoochee–Flint River Basin and conceptualization of ground-water flow (from Torak and others, 1996).

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}+T_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}+T_{yy}\frac{\partial h}{\partial y}\right)+K'_{zz}\frac{\partial h'}{\partial z}+P=S\frac{\partial h}{\partial t}\ , \qquad (1)$$

where:

(x,y,z)=Cartesian coordinate directions [length];

t=time;

$h(x,y,t)$=hydraulic head in aquifer [length];

$h'(x,y,t)$=hydraulic head in semiconfining unit [length];

$K'_{zz}(x,y,z)$=vertical hydraulic conductivity of semiconfining unit [length/time];

$S(x,y,t)$=aquifer storage coefficient [dimensionless];

$\begin{bmatrix} T_{xx}(x,y,t) & T_{xy}(x,y,t) \\ T_{yx}(x,y,t) & T_{yy}(x,y,t) \end{bmatrix}$=symmetric transmissivity tensor written in matrix form [length^2/time]; and

$P(x,y)=\sum_{j=1}^{p}\delta(x-a_j)\,\delta(y-b_j)$=Dirac-delta designation for p point sources or sinks, each of strength Q_j [length/time] and located at (a_j, b_j). Q_j is positive for injection.

Boundary and Initial Conditions

Equation 1 is subject to the following boundary and initial conditions:

(1) At a discontinuity in transmissivity (an internal boundary) the normal component of ground-water flow and the hydraulic head are unchanged as the discontinuity is crossed (Bear, 1979, p. 100–102).
(2) The normal component of flow at a hydrologic boundary is given by the sum of a specified component, q_B, and a head-dependent component, $\alpha(H_B–h)$ (Bear, 1979, p. 117–12), where q_B and $\alpha(H_B–h)$ are unit-discharge rates [length^2/time], positive for inflow, or, volumetric flow rates [length^3/time] per unit length along the boundary; H_B is a specified head controlling the flow rate; and α is a parameter equal to “infinity” for a specified head (Dirichlet) condition, zero for a specified flow (Neumann) condition, and a finite, positive value for a general (Cauchy) condition.
(3) The initial hydraulic head is known everywhere for the steady-state period.

Steady-state and nonsteady-state, or transient, conditions are represented in equation 1. For steady-state flow, there is no release or uptake of water due to elastic-storage effects in either the aquifer or semiconfining unit, and flow is time invariant. The steady-state equation is derived from equation 1 by setting the aquifer-storage term, $S\,\partial h/\partial t$, to zero, and by representing the leakage flux, $K'_{zz}(\partial h'/\partial z)$, or flow rate across the vertical boundary between the aquifer and semiconfining unit, with a steady-leakage term, $R(H–h)$, where $R = R(x,y)$ is the vertical hydraulic conductance of the semiconfining unit (vertical hydraulic conductivity divided by its thickness) [time^{-1}] and $H=H(x,y,t)$ is hydraulic head [length] in the source layer. Flow in the semiconfining unit is assumed to be nearly vertical. The source layer, which contains H, is located either within the semiconfining unit or beyond it, and provides the potential for flow through the semiconfining unit.

Artesian (linear) and water-table (nonlinear) conditions both exist in the Upper Floridan aquifer and Intermediate system and are represented by equation 1. Ground-water flow under artesian conditions is linear (with linear boundary conditions), because terms that multiply either aquifer hydraulic head $h(x,y,t)$ or derivatives of head do not depend on head values. Water table, or semiconfined, conditions produce nonlinear flow with nonlinear boundary conditions, because some terms in equation 1 depend on aquifer head, such as transmissivity (a function of saturated-aquifer thickness, which depends on hydraulic head), and steady-vertical leakage. The nonlinearity in steady-vertical leakage is caused by the aquifer changing from artesian to water table or from water table to artesian, which changes the form of the leakage expression, $R(H–h)$.

The terms q_B and $\alpha(H–h)$, in boundary-condition 2, above, are unit discharges across an aquifer-zone boundary. A zone might define either a discontinuity in aquifer properties, such as a lateral change in transmissivity, or the outer boundary to the aquifer or study area. Each term is a special case of the Cauchy-boundary condition, called a “Cauchy-type” boundary (Norrie and deVries, 1973; and Cooley, 1983), because the specified-head component is not represented in the $\alpha(H_B–h)$ term. Linear and nonlinear forms of Cauchy-type boundaries are used to represent lateral-boundary conditions in the study area. Details of specific applications are given in the following sections.

Numerical Model

The numerical model used to simulate ground water flow in the Upper Floridan aquifer and water-bearing units of the Intermediate system is the MODdular Finite Element model (MODFE) of the USGS (Cooley, 1992; and Torak, 1993a,b). The governing equation and boundary conditions given above are approximated in MODFE, and the approximate solutions of hydraulic head are obtained at the intersections of element sides, which are called nodes.

Simulation Approach

To achieve study objectives, simulation of ground-water flow with surface-water relations under steady- and nonsteady-state (transient) conditions was performed. Finite-element models of two-dimensional, steady-

state, ground-water flow for the aquifer-stream-reservoir system, which were developed in a previous study (Torak and others, 1996), were used as the basis for simulation in this study. The Upper Floridan model simulates ground-water flow in the aquifer and its interaction with surface water, as conceptualized in the northern and central parts of the study area (figs. 17; 18). The Intermediate model simulates flow in water-bearing units of the Intermediate system and its interaction with surface water, as conceptualized in the southern part of the study area (fig. 19). Steady-state simulations quantified the water-resource potential and effects of changing specific hydrologic characteristics on stream-aquifer relations in the Upper Floridan and Intermediate models. Model inputs defining boundary conditions and stresses to the ground-water-flow system were changed simultaneously so that simulations reflect hydrologic conditions that either might have existed or might exist sometime in the future. A transient version of the Upper Floridan model was used to estimate flow-system response to potential “real-time” changes in pumpage.

In the Upper Floridan model, the Upper Floridan aquifer was represented in MODFE as the model layer for which hydraulic head was computed; thus simulating two-dimensional, horizontal, ground-water flow. The overlying semiconfining unit, comprised of terrace and undifferentiated (surficial) deposits and undifferentiated overburden (fig. 4), was simulated in MODFE by using a steady-vertical-leakage function, which provided recharge to, and discharge from, the Upper Floridan aquifer. Source-layer head for this leakage was assigned as the top of the lower-half thickness of clayey sediments in the semiconfining unit and was held constant for all simulations. Field observations indicated that the clayey sediments were saturated during October 1986; thus, dewatering of these sediments was negligible during the drought. The vertical boundary of the simulated aquifer with the lower confining unit (Lisbon Formation, fig. 4) was simulated as a no-flow boundary, as the Lisbon Formation is an effective impermeable base to the stream-aquifer system. These details of the simulation approach for the Upper Floridan model are summarized in the following table:

Upper Floridan model

Hydrologic unit (fig. 4)	Simulation approach
Semiconfining unit	Steady vertical leakage
Upper Floridan aquifer	Simulated model layer
Lower confining unit	No-flow boundary

Other hydrologic characteristics of the stream-aquifer system in the Upper Floridan model, namely, regional ground-water flow, flow across streambeds, and springflow, were simulated in MODFE by using mathematical boundary conditions to ground-water-flow equation 1 that account for recharge to, or discharge from, the simulated Upper Floridan aquifer. In addition, the outcrop area of the Upper Floridan aquifer was represented with specified-head boundaries. Regional inflows and ouflows were represented with computations that simulated lateral flow across boundaries of the Upper Floridan aquifer with aquifer material located beyond the model area. Flow across streambeds was simulated in MODFE as either aquifer discharge to, or recharge from, streams by using computations that involve the hydraulic properties and general geometry of the streambed, and relative head differences between stream stage and the Upper Floridan aquifer. Simulation of in-channel springflow was combined with flow across streambeds, as hydrologically, and mathematically, both are identical features that cause aquifer discharge to streams. Off-channel springflow was simulated in a manner identical to well discharge because both wells and springs are point discharges in the aquifer; thus, a point-discharge function in MODFE was used to simulate these hydrologic features.

In the Intermediate model, the Intermediate system was represented in MODFE as the model layer for which hydraulic head was computed; thus, simulating two-dimensional, horizontal, ground-water flow. In this part of the basin, the Upper Floridan aquifer and sub-Floridan confining unit (fig. 4) are stratigraphically too deep to be considered part of the stream-aquifer system. Consequently, neither of these hydrologic units were represented in MODFE as the model layer to be simulated. Steady vertical leakage through overlying and underlying semiconfining units and through lakebeds was simulated in MODFE to provide recharge to, and discharge from, the Intermediate system. The hydraulic potential for vertical leakage was provided by appro-

priate values of source-layer head that represent the overlying semiconfining unit (fig. 4), underlying Upper Floridan aquifer, and lake levels. Head in semiconfining units and lake levels were nearly constant in the southern part during October 1986; therefore, source-layer head was held constant in the Intermediate model. Details of the simulation approach for the Intermediate model are summarized in the following table:

Intermediate model

Hydrologic unit (fig. 4)	Simulation approach
Overlying semiconfining unit	Steady vertical leakage
Intermediate system	Simulated model layer
Underlying semiconfining unit	Steady vertical leakage
Upper Floridan aquifer	Source layer; steady vertical leakage
Sub-Floridan confining unit	Not simulated

In the Intermediate system, well discharge was negligible, and springflow was nonexistent; therefore, they were not simulated in the Intermediate model. Stream-aquifer relations were simulated in the Intermediate model as vertical flow across streambed sediments in the identical manner as that used in the Upper Floridan model.

Steady-State Analysis

Steady-state simulations were used to evaluate long-term effects of sustained changes in hydrologic conditions, such as a decrease in stream stage or pool altitude and changes in pumping rates, on downstream baseflow in the lower ACF River Basin. Emphasis was placed on examining the effect of a wide range of pumpage and other hydrologic parameters on computed stream-aquifer flows. In particular, the following three hydrologic characteristics pertinent to the functioning of the aquifer-stream-reservoir system were analyzed through simulation: hydraulic head in semiconfining units, stream stage, and ground-water pumpage. In addition to meeting study objectives, a goal of these simulations was to provide water managers with a means of forecasting changes in stream-aquifer flow based on observable conditions of pumpage, stream stage, and hydraulic head in semiconfining units to the Upper Floridan aquifer.

Sensitivity analysis of hydrologic characteristics assumed to affect water-resource potential of the aquifer-stream-reservoir system, performed through simulation and reported in Torak and others (1996), indicated moderate sensitivity of computed head in the Upper Floridan model to changes in semiconfining-unit head and stream stage. Although changes in pumpage of less than twice the October 1986 rates did not cause noticeable changes in computed hydraulic head from October 1986 conditions, increased pumpage in the sensitivity analysis caused notable stream-aquifer-flow declines in the Upper Floridan model. Therefore, evaluation of stream-aquifer-flow declines caused by simultaneous changes to pumping rates, stream stage, and semiconfining-unit head was needed and, hence, served as the basis for steady-state simulations performed using the Upper Floridan model.

Computed head in the Intermediate system was relatively insensitive to changes in vertical-boundary (source-layer) head in the underlying Upper Floridan aquifer, and moderately sensitive to head change in the overlying semiconfining unit. Thus, head changes for the overlying semiconfining unit were made only at locations where this unit was in direct hydraulic connection with, or constituted, a water table in the flood plain, and was connected hydraulically to the Chipola and Apalachicola Rivers. Changes to the potentiometric surface of the Upper Floridan aquifer beneath the Intermediate system, in response to pumpage increases in the Upper Floridan model, were expected to be negligible because head declines of about a foot or less were computed in the Upper Floridan aquifer at the boundary of the two models (Torak and others, 1996). Therefore, changes to head in the underlying Upper Floridan aquifer were not made for the steady-state analysis of the Intermediate model. Because pumpage is negligible in water-bearing units of the Intermediate system, it was not changed in the steady-state analysis using the Intermediate model; the analysis involved

systematic changes only to stream stage and semiconfining-unit head and evaluation of the resulting changes in stream-aquifer flow.

To incorporate changes in pumpage, stream stage, and semiconfining-unit head systematically into an analysis involving steady-state simulations, matrices listing the attributes of each simulation were developed for the Upper Floridan and Intermediate models (tables 1, 2). Each member in a row, (R1 to R6), of the “simulation matrix” for the Upper Floridan model (table 1) represents a steady-state simulation involving identical hydraulic properties of the flow system except for variations in ground-water pumpage, which is differentiated in the matrix by columns P0 to P5. Pumpage was adjusted as multiples of the October 1986 rates that were used in a previous model study (Torak and others, 1996). Multipliers of 0 (zero-pumpage, reference conditions), 0.5, 1, 2, and 5, were applied to nodal pumping rates to simulate likely pumpage distributions that might occur in the study area under drought conditions and increased ground-water development. Because increases solely to head in the semiconfining-unit from “dry” (October 1986) to “normal” (long-term average) conditions would provide an unnatural source of water to the aquifer, resulting in unrealistic discharge of ground water across lateral model (and basin) boundaries, heads that drive lateral-boundary flow into and out of the Upper Floridan model were increased along with semiconfining-unit head; both conditions are listed in the simulation matrix (table 1).

For the Intermediate model, each member of the simulation matrix (table 2) represents a unique and plausible combination of semiconfining-unit head and stream stage. The relative insensitivity of the Intermediate model to changes in lateral-boundary head, coupled with head changes in the Intermediate system from “dry” to “normal” conditions of less than 3 ft at sparsely distributed wells, permitted changes in lateral-boundary head to be neglected in the Intermediate model. Hence, only changes to stream stage and head in the overlying semiconfining-unit were made for steady-state analysis of the Intermediate model.

Three surface-water conditions were superposed onto changes in boundary and semiconfining-unit head in the simulation matrices (tables 1, 2), namely, October 1986, Q_{90}, and Q_{50} conditions. The October 1986 conditions represented low-flow, low-stream-stage conditions, and the Q_{nn} conditions represented stream stage for flow that was exceeded *nn* percent of the time. On some streams, surface-water records indicated that streamflow for October 1986 represented a flow that was lower than Q_{98}, therefore, October 1986 was suitable for representing drought conditions in the surface-water system as well as in the ground-water system.

Ground-water pumpage varied as multiples of October 1986 rates for simulations using the Upper Floridan model (table 1). Reference simulations of zero pumpage were performed to provide a means of comparing water-budget components, principally, stream-aquifer flow, among simulations in each row. Although it is possible for the zero-pumpage scenarios to represent prepumpage conditions in the lower ACF River Basin, it is unlikely that any of the combinations of boundary and semiconfining-unit head and stream stage given in the matrices actually existed simultaneously in the basin prior to the inception of pumpage. Five multiples of October 1986 pumping rates were simulated for each row of the simulation matrix, including the zero-pumpage scenarios, totalling 30 steady-state simulations for the Upper Floridan model, and 6 steady-state simulations of the Intermediate model, giving a total of 36 simulations for the steady-state analysis.

Limitations

Because steady-state ground-water flow is neither time dependent nor time variant, hydrologic effects of releasing water from, or taking water into, storage within aquifers, semiconfining units, and riverbeds and lakebeds are neglected in a steady state analysis. These effects produce a time delay, or lag, in the flow-system response to changes in stress as hydrologic units equilibrate to new steady state conditions. The inability to represent this time lag is manifested in the inability of steady-state models to simulate storage effects in aquifers and semiconfining units. This inability can be viewed as a disadvantage if time-variant-flow conditions are needed to make sound water-resource-management decisions.

Table 1. Simulation matrix for steady-state analysis using Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin

[Matrix elements identified by row number, R1–R6, and column, P*n*, where *n* defines multiple of October 1986 ground-water pumping rate, *n*=0, .5, 1, 2, 5; ref. is zero-pumpage, reference condition; Q_{nn} is streamflow that is exceeded *nn* percent of the time]

Simulation Matrix—Upper Floridan Model

Reduction in Stream-Aquifer Flow Scenario 1—Stream Stages at October 1986 Drought Level

Boundary & semi-confining unit head condition	Pumpage (x October 1986 rate)				
	0 (ref.)	0.5	1	2	5
Dry[1]	R1P0	R1P.5	R1P1	R1P2	R1P5
Normal[2]	R2P0	R2P.5	R2P1	R2P2	R2P5

Reduction in Stream-Aquifer Flow Scenario 2—Stream Stages at Q_{90} Level

Dry[1]	R3P0	R3P.5	R3P1	R3P2	R3P5
Normal[2]	R4P0	R4P.5	R4P1	R4P2	R4P5

Reduction in Stream-Aquifer Flow Scenario 3—Stream Stages at Q_{50} Level

Dry[1]	R5P0	R5P.5	R5P1	R5P2	R5P5
Normal[2]	R6P0	R6P.5	R6P1	R6P2	R6P5

[1] Equivalent to October 1986 conditions.

[2] Long-term-average conditions based on period of record at wells.

Advantages

Steady-state conditions of low-flow and low-water level (October 1986) provide an opportunity to obtain conservative estimates (to observe worst-case conditions) of long-term effects of ground-water development on the aquifer-stream-reservoir system. Increased ground-water pumpage imposes additional stress on a flow system that already exhibits and has equilibrated to low-flow and low-water-level conditions; hence, the aquifers are forced to equilibrate to hydrologic conditions that are beyond that which might occur in the basin during normal circumstances of precipitation, pumpage, and streamflow. Through simulation, hypothetical stresses are sustained until new, synthetic, steady-state conditions are established in the flow system.

Table 2. Simulation matrix for steady-state analysis using Intermediate model of the lower Apalachicola-Chattahoochee-Flint River Basin

[Matrix elements identified by row number, R1 or R2, and stream stage, where OCT is October 1986 stage, and Q_{nn} is stage for flow that is exceeded *nn* percent of the time]

Simulation Matrix—Intermediate Model

Reduction in Stream-Aquifer Flow Scenarios—No Pumpage

Semiconfining-unit head condition	Stream-aquifer-flow scenario–stream stage		
	October 1986	Q_{90}	Q_{50}
Dry[1]	R1POCT	R1Q90	R1Q50
Normal[2]	R2POCT	R2Q90	R2Q50

[1] Equivalent to October 1986 conditions.

[2] Long-term-average conditions based on period of record at wells.

Thus, conservative estimates of the potential for increased ground-water development and the effects of this development on other uses for water resources in the basin are obtained from the steady-state analysis.

Transient Analysis

The goal of the transient simulations was to quantify the existence of any temporal lag in pumpage-induced, stream-aquifer-flow declines as increases to ground-water pumpage are simulated. The pertinent question that was addressed was whether increases in ground-water withdrawal results in instantaneous decreases in stream-aquifer flow. Transient simulation was used to estimate times between pumpage increases and stream-aquifer-flow reductions (Harold F. Reheis, Director, Georgia Department of Natural Resources, Environmental Protection Division, written commun., June 1993).

Results from the calibrated finite-element model developed in a previous study of stream-aquifer relations in the lower ACF River Basin (Torak and others, 1996) were used as an initial condition for transient simulations that were performed to define the time lag between changes in pumping rates and resultant changes in stream-aquifer flow. Pumpage at the October 1986 rate (475 Mgal/d) was reduced to zero at the beginning of the transient simulations, and the time for stream-aquifer flows to adjust to a new condition of hydrologic equilibrium was determined. Setting pumping rates to zero in this manner is representative of conditions that occur annually in the lower ACF River Basin at the end of each growing season, such as in November, particularly in the Dougherty Plain physiographic district. However, results of this time-lag determination are useful in defining the transient response of the flow system to pumpage increases, as well as decreases, that might occur throughout the growing season, as explained below.

Results of the sensitivity analysis performed by using the calibrated model (Torak and others, 1996), indicated that the hydrologic system responds to pumpage in a uniform, linear manner; that is, doubling the pumping rate resulted in doubling ground-water-level declines (aquifer drawdown) and halving ground-water flow to streams. Linear-aquifer response also was exhibited in water-budget components, which were computed for each simulation, including reduced discharge to streams. These values indicated that reduced discharge to streams contributed nearly a constant percentage of the simulated-increased pumping rates, for

pumpage increases that were less than 5 times the October 1986 rates. The same linear-flow-system behavior is expected at other times during the growing season when ground- and surface-water levels are higher than in October, despite increased pumpage during the growing season. This linear flow-system response to pumpage is advantageous to a transient analysis of stream-aquifer-flow decline because it indicates that the hydrologic effects of pumpage on the flow system are reversible; the aquifer will exhibit an equal, but opposite, response to pumpage changes that are in equal, but opposite, directions. That is, transient-response times for the aquifer-stream-reservoir system are identical for pumpage increases and decreases of the same magnitude and spatial distribution. Hence, the time lag and increase in stream-aquifer flow caused by a pumpage decrease is defined by the time lag and stream-aquifer-flow decline obtained for a pumpage increase of the same magnitude and spatial distribution.

Because the digital model was prepared for October 1986 hydrologic conditions, these conditions are used as the basis for the transient analysis. An advantage of starting from a known, steady-state, calibrated set of hydrologic conditions, October 1986, is that the digital model can be used to evaluate changes in stream-aquifer flow that result solely from changes in pumpage. If another set of hydrologic conditions was used, then the flow system would have to equilibrate to those conditions, as they are different from the October 1986 conditions, in addition to responding to pumpage changes. For this case, the resulting time lag would represent the transient response of the flow system to changes in hydrologic conditions, as well as to changes in pumpage, and, therefore, would not meet the goal of this analysis.

A further advantage of analyzing the transient response of a linear flow system to pumpage change instead of a nonlinear flow system is that the time lag for a linear system to equilibrate to a new steady-state condition is not dependent on temporal, pumpage induced changes in hydraulic characteristics. Therefore, time lags for a linear system are identical regardless of whether the aquifer responds to an increase or a decrease in pumpage. The temporal lag in pumpage-induced stream-aquifer flow that might exist, for example, during the growing season, occurs at the same rate for pumpage changes having different magnitudes and direction but the same spatial distribution. Thus, to extend the example, the time lag required for the hydrologic system to respond to a termination of pumpage at the end of a growing season is identical to the time lag associated with doubling the pumping rates during the growing season, given the same spatial distribution of pumpage. Therefore, the time lag for the hydrologic system to respond to pumpage increases can be obtained by simulating the recovery of the flow system due to pumpage cessation, which was performed in this analysis.

Finite-Element Mesh

A finite-element mesh, a network of triangular elements, was constructed for each model area in the lower ACF River Basin to represent variations in hydraulic properties, boundary geometry, surface-water features, and hydraulic head (pl. 4). The finite-element mesh for the Upper Floridan model consists of 12,295 elements and 12,113 nodes; the mesh for the Intermediate model contains 4,024 elements and 3,963 nodes. Physical boundaries of the lower ACF River Basin were used as limits for the finite-element mesh in each area. Hydrologic boundaries to both models were defined from general patterns of ground-water movement and from stream-aquifer relations as described previously, and are depicted in figures 17–19.

The meshes contain mostly equilateral triangles of two sizes, 2,083 and 4,167 feet on a side. Selection criteria for suitable element sizes were based on the ability of computed head to represent curves in the potentiometric surface caused by spatial and temporal changes in stress, boundary conditions, and aquifer geometry. Smaller elements permitted details in computed hydraulic head, aquifer geometry, and aquifer-property variability to be represented more accurately than larger elements; hence, smaller triangles were used along curved stream reaches and in the adjacent aquifer. In addition, some elements were adjusted from the uniform equilateral-triangular shape by moving nodes so that specific flow-system geometries were represented, such as tight meanders of stream reaches or irregular shapes in the external-model boundary. Thus, with selected-node movement, the size of element sides ranged from about 1,100 ft to 4,750 ft.

Boundary Conditions

Lateral and vertical hydrologic boundaries consisting of regional ground-water flow, flow across streambeds, and vertical leakage for the two model areas were represented in MODFE by using the head-dependent part of a Cauchy-type boundary and specified-head boundaries. Line and areally distributed forms of the Cauchy-type boundary represented regional ground-water flow, flow across streambeds, and steady vertical leakage through semiconfining units and areally extensive riverbeds and lakebeds. Linear and nonlinear forms of these boundary conditions were used depending on whether unconconfined- (water-table) aquifer conditions existed or were anticipated, or if specific rivers were expected to go dry, thus eliminating a source of recharge to the aquifer. Detailed descriptions of the Cauchy-type boundaries used in the Upper Floridan and Intermediate models to represent linear and nonlinear line- and areal-head-dependent leakage are given in Cooley (1992) and Torak (1993a,b). Applications of these boundary conditions to the lower ACF River Basin are described in Torak and others (1996). Brief summaries based on these reports are given below.

Regional Ground-Water Flow

Regional inflow and outflow across external model boundaries were represented in MODFE by using the head-dependent part of a Cauchy-type boundary and by specified-head boundaries (Torak, 1993a). The head-dependent part of a Cauchy-type boundary linearly relates the volumetric-flow rate across the boundary to a head difference. For regional flow, a controlling head is positioned in the aquifer outside the model area and is unaffected by simulated water-level changes at the model boundary. The linear relation between the head difference and flow rate is achieved by a resistance-to-flow term, α, described previously for boundary-condition 2. This term contains the linear combination of hydraulic properties that govern advective ground-water flow in the aquifer material between the model boundary and external head, which is located a distance of about 3 mi from the model boundary. Values of α are specified either by element side or by zone, where a zone is a collection of element sides containing the same hydraulic properties. Zone values of α used in the calibrated models are listed in table 3, and zones are shown on plate 4.

Specified-head boundaries were used to represent ground-water levels and regional-flow components in the outcrop area of the Upper Floridan aquifer. These boundaries were represented in MODFE by using nodes of the finite-element mesh (pl. 4) that were assigned values corresponding to water levels in the Upper Floridan aquifer in late October 1986. Water levels at these nodes were held constant for the steady-state and transient simulations. In addition to specified-head-boundary nodes, a slightly different form of specified head condition is defined by the external head contained in the head dependent parts of the Cauchy-type boundaries used in the models. The external head is fixed along these boundaries, although separated hydraulically from the model-area boundary by the flow-resistance term, α, described previously.

Because the Upper Floridan and Intermediate models simulate ground-water flow in different hydrologic units, regional outflow along the southern boundary of the Upper Floridan model does not correspond with inflow along the northern boundary of the Intermediate model, even though these boundaries are coincident (pl. 1). The aquifers simulated in each model are not connected hydraulically by lateral flow. Instead, they are connected by vertical leakage through overlying and underlying semiconfining units. The models are linked hydraulically by vertical leakage across streambeds that are in contact with the simulated aquifers.

Flow Across Streambeds

Flow across streambeds was represented by linear and nonlinear forms of a Cauchy-type boundary (Torak, 1993a). The linear form of this boundary enabled simulation of ground-water recharge and discharge across streambeds based on the relative difference between aquifer head and stream stage, but did not simulate dry-stream conditions. Dry-stream conditions were represented by the nonlinear form, which did not permit ground-water recharge to the aquifer if the aquifer head was below the bottom of the streambed. The nonlinear form of Cauchy-type boundary was used to represent stream reaches that either contained small upstream flows or were partially dry during October 1986, and to represent large streams and rivers if the po-

Table 3. Head-dependent (Cauchy-type) boundaries of calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin, by zone (from Torak and others, 1996)
[Zones shown on plate 4]

Upper Floridan model			Intermediate model		
Zone(s)	**Boundary coefficient, (feet/day)**	**Description**	**Zone(s)**	**Boundary coefficient, (feet/day)**	**Description**
1, 2	0.13	Flint River	59-61	6.0 to 12	Apalachicola River
3	.06	Flint River	62	2.0	Chipola River, upstream of Dead Lake
4	5.0	Lake Worth	63	2.0 to 3.0	Chipola River and cutoff, downstream of Dead Lake
5	100	Flint River at Flint River Dam	64	2.5	Brothers River
6	1,000 to 2,000	Flint River at Albany, Ga.	65	5.0	St. Marks River
7-17	100 to 500	Flint River downstream of Albany, Ga., to Lake Seminole	66	5.0	East River
18, 19	10 to 12	Muckalee Creek[1/]	67	2.5	Jackson River
20-24	2.0 to 6.0	Muckalee Creek[1/]	68	5.0	Cypress Creek
25	8.0	Muckaloochee Creek[1/]	69	0.64 to 3.0	Northern model boundary; regional flow
26-31	0.5 to 6.0	Kinchafoonee Creek[1/]	70	2.0	Northwestern model boundary; regional flow
32	18	Ichawaynochaway Creek[1/]	71	1.0	Southwestern model boundary; regional flow
33	4.5	Ichawaynochaway Creek[1/]	72	1.0 to 2.0	Southern model boundary; regional flow
34, 35	10	Ichawaynochaway Creek[1/]			
36	18	Patchitla Creek[1/]			
37	2.0	Chattahoochee River			
38, 39	60 to 100	Chattahoochee River			
40	150	Chattahoochee River			
41-45	12 to 20	Chipola River			
46	6.0	Chipola River			
47-50	6.0 to 12	Apalachicola River			
51	30	Southwestern model boundary; regional flow			
52	30	Southern model boundary; regional flow			
53	55	Southeastern model boundary; regional flow			
54	55	Eastern model boundary, southern part; regional flow			
55	120	Eastern model boundary, northern part; regional flow			
56	100	Northeastern model boundary; regional flow			
57	45	Northeastern model boundary; regional flow			
58	0 to 35	Northeastern model boundary; regional flow			

[1/] Tributary to Flint River.

tential existed for simulated ground-water levels to drop below the bottom of the streambed, causing a dry stream. This representation is consistent with the concept that upland reaches of streams in the northern part of the lower ACF River Basin only drain the Upper Floridan aquifer and do not provide a source of water to the aquifer if ground-water levels are below the streambed, and also is consistent with dry stream reaches that were observed in upland areas during late October 1986.

Flow across streambeds is a function of vertical hydraulic conductivity of the streambed sediment, width of the surface-water feature, sediment thickness, and the relative difference between the aquifer water

level and stream stage. The geometric and hydraulic characteristics of the streambed (vertical hydraulic conductivity, and streambed width and thickness) are combined in one flow-resistance term, α, which was defined previously for boundary condition 2. Values of are specified either by reach (element side) or by zone, as in the linear case, where a zone is a collection of reaches containing the same hydraulic properties. Zones used to represent nonlinear Cauchy-type boundaries (streams) are identified on plate 4, and calibrated values of α for linear and nonlinear boundaries are listed in tables 3 and 4.

Vertical Leakage

Vertical leakage across aquifer boundaries with overlying and underlying semiconfining units was represented in MODFE by functions that simulate areal, head-dependent, steady leakage, either with or without aquifer dewatering, and transient leakage of water stored elastically in a semiconfining unit. Details of the numerical formulation of these boundary conditions in MODFE are given in Cooley (1992), and a description of their implementation in MODFE is given in Torak (1993a,b). Application of steady-vertical-leakage functions to the flow system in the lower ACF River Basin is described in Torak and others (1996), for the Upper Floridan and Intermediate models, and is summarized briefly in this section.

Areal, steady vertical leakage without storage effects from semiconfining units was used in steady-state simulations of the Upper Floridan and Intermediate models. The general form of steady-vertical leakage is given by the term $R(H–h)$, derived from equation 1, and was used in the steady-state analysis of the Intermediate model to represent semiconfining units that underlie water-bearing zones of the Intermediate system. Nonlinear forms of steady-leakage functions were used in the Upper Floridan and Intermediate models to limit recharge to the aquifers to a maximum rate when aquifer head drops below the base of the overlying semiconfining units, or below the top of the aquifers if water-table conditions occur. Discharge from aquifers to overlying semiconfining units was not limited by the nonlinear form. Because the Upper Floridan aquifer was conceptualized as having an impermeable base, only the overlying semiconfining units to the Upper Floridan aquifer were represented with vertical leakage; underlying units were excluded from the model.

Values used for model inputs to simulate linear and nonlinear steady vertical leakage are identical to those used in the models developed previously for the lower ACF River Basin by Torak and others (1996). Zone values of hydraulic conductance used in the calibrated models are listed in table 5. To facilitate model input, zone boundaries that define the general distribution of clay thickness in semiconfining units overlying the Upper Floridan and Intermediate models were established by using element sides of the finite-element mesh (pl. 2). Additional zones were defined where clay thickness was zero, or where the unit either was absent or had a total thickness of less than 10 ft. These zones were given a unique zone number (=1) and assigned a vertical hydraulic conductance of zero (pl. 5), as it was assumed that the sediments could neither supply enough water nor act as a semiconfining unit to the simulated aquifers. Zones of vertical hydraulic conductance for the underlying semiconfining unit to the Intermediate system are shown on plate 6.

A transient-leakage approximation accounting for elastic-storage effects of semiconfining units was used in the transient analysis of the Upper Floridan model to represent flow to and from overlying semiconfining units and across bottom sediments of Lake Seminole in response to pumpage. Only the Upper Floridan model was involved in the transient analysis because the Intermediate model contained no pumpage. The approximation provided values for the vertical-leakage flow, $K'_{zz}(\partial h'/\partial z)$, of equation 1, which was evaluated at the boundary of the semiconfining unit with the aquifer and governs the establishment and dissipation of nonsteady, vertical hydraulic gradients in the semiconfining unit with time. Storage properties in the semiconfining units are responsible for the transient behavior, and the combination of simulation time and vertical hydraulic conductivity, specific storage, and thickness of the semiconfining unit collectively determines the nature of the transient-aquifer response (temporal head changes) caused by pumpage or other stresses. A nonlinear form of the transient-leakage approximation limits the head change at nodes where the aquifer converts from confined to unconfined (water-table) conditions. Details of the transient-leakage approximation are given in Cooley (1992) and Torak (1993a,b).

Table 4. Nonlinear head-dependent (Cauchy-type) boundaries of calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin, by zone (from Torak and others, 1996)
[Zones shown on plate 4]

Zone(s)	Boundary coefficient, (feet/day)	Description
1	0.5	Limestone Creek[1/]
2-3	1 to 2	Gum Creek[1/]
4	2 to 3	Gum Creek[1/]
5-8	0.6 to 1	Cedar Creek[1/]
9	1	Swift Creek[1/]
10	2	Swift Creek[1/]
11	1	Swift Creek, North Branch[1/]
12-14	0.75	Jones Creek[1/]
15-16	1	Abrams Creek[1/]
17-19	3.5	Mill Creek[1/]
20-25	1.8 to 2	Cooleewahee and Chickasawhatchee Creeks[1/]
26-28	1.5 to 1.8	Chickasawhatchee Creek[1/]
29-31	0.5	Spring Creek
32, 33	2	Spring Creek
34	8	Spring Creek
35	27	Spring Creek
36	32	Spring Creek
37, 38	0.2	Dry Creek
39	1	Dry Creek
40	2.5	Dry Creek
41-43	1.3 to 2	Sawhatchee Creek
44, 45	5	Cowarts Creek
46, 47	5	Marshall Creek
48-50	16	Dry Creek (Fla.)
51-54	5	Tenmile and Fourmile Creeks
55, 56	6	Juniper Creek

[1/] Tributary to Flint River.

Model inputs of vertical hydraulic conductivity and specific storage for the semiconfining unit used to simulate transient leakage in the Upper Floridan model were obtained from previous inputs used for steady leakage, and from inferences about the compressibility of the confining-bed matrix and interstitial fluid (water). Values of vertical hydraulic conductivity were computed by multiplying zone values of vertical hydraulic conductance (table 5) by thickness of the semiconfining unit, shown on plate 2. Because no hydrologic analyses were reported in the literature about specific storage of semiconfining units, it was assumed that a semiconfining unit is at least as elastic (compressible) as the water that it conveys. Therefore, values of specific storage were set selected slightly larger than the inverse of the volume modulus of elasticity, or bulk modulus (Daugherty and Franzini, 1977; chapter 1), of water under aquifer conditions of temperature and pressure. Thus, specific storage in the range $5\text{x}10^{-6}$ to $5\text{x}10^{-5}\text{ft}^{-1}$ was used in the transient analysis to test a range of plausible semiconfining-unit-storage values and evaluate their effects on the time-lag determination.

Nodal values for the source layer head, *H*, were input to the Upper Floridan model as the altitude of the ground-water level above clay or clayey sediments in the lower half of the undifferentiated overburden. It was assumed that only the clay in the lower half of the overlying semiconfining units in the Upper Floridan

Table 5. Zone values of vertical hydraulic conductance for semiconfining units in calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin (from Torak and others, 1996)
[Vertical hydraulic conductance in feet per day per foot]

Upper Floridan model						Intermediate model			
Overlying semiconfining unit (zones on plate 5)						Overlying semiconfining unit (zones on plate 5)		Underlying semiconfining unit (zones on plate 6)	
Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance	Zone	Vertical hydraulic conductance
1	0	14	$5.2x10^{-6}$	27	$1.1x10^{-4}$	39	0	1	$1.5x10^{-4}$
2	$8.4x10^{-10}$	15	$8.4x10^{-6}$	28	$2.0x10^{-4}$	40	$8.4x10^{-6}$	2	$1.5x10^{-4}$
3	$6.7x10^{-9}$	16	$9.5x10^{-6}$	29	$2.1x10^{-4}$	41	$1.1x10^{-5}$	3	$7.5x10^{-4}$
4	$9.0x10^{-9}$	17	$1.3x10^{-5}$	30	$2.5x10^{-4}$	42	$1.4x10^{-5}$	4	$7.5x10^{-4}$
5	$5.5x10^{-8}$	18	$2.0x10^{-5}$	31	$3.0x10^{-4}$	43	$2.1x10^{-5}$	5	$7.5x10^{-4}$
6	$3.4x10^{-7}$	19	$2.1x10^{-5}$	32	$3.8x10^{-4}$			6	$3.0x10^{-4}$
7	$4.2x10^{-7}$	20	$3.0x10^{-5}$	33	$4.0x10^{-4}$			7	$7.5x10^{-4}$
8	$5.0x10^{-7}$	21	$5.0x10^{-4}$	34	$5.0x10^{-4}$			8	$3.0x10^{-4}$
9	$6.7x10^{-7}$	22	$4.7x10^{-5}$	35	$6.1x10^{-4}$			9	$7.5x10^{-4}$
10	$1.7x10^{-6}$	23	$5.0x10^{-5}$	36	$8.4x10^{-4}$				
11	$2.1x10^{-6}$	24	$6.7x10^{-5}$)	37	$9.8x10^{-4}$				
12	$2.5x10^{-6}$	25	$9.4x10^{-5}$	38	$8.0x10^{-3}$				
13	$4.2x10^{-6}$	26	$1.0x10^{-6}$						

model was saturated in October 1986, due to the seasonal and near record-low ground-water levels that existed in the basin at that time. Because water-level measurements were sparse in the overlying semiconfining unit to the Intermediate model, source-layer head was estimated to be 5 ft below land surface altitude. The water table of the surficial sediments functioned as the source layer head in the Intermediate model.

Springflow

Ground-water discharge to springs, or springflow, was simulated in the Upper Floridan model with two different mathematical representations; the point-discharge function, *P*, in equation 1, and the head-dependent part of a Cauchy-type boundary. The point-discharge function simulates springflow in the identical manner as point withdrawals from wells. The head-dependent part of a Cauchy-type boundary incorporates springflow into aquifer discharge along a stream reach. The selection of which mathematical representation to use for a spring was based on whether or not the spring discharged directly into a stream channel (in-channel spring), or whether spring discharge occurred at some distance away from a stream (off-channel spring). Springs are not present in the Intermediate system, therefore, only the Upper Floridan model simulates springflow.

Springs in Gadsden, Jackson, and Liberty Counties, Fla., were represented as off-channel springs; thus, they were simulated using point-discharge functions. Locations and discharge rates of springs in the Upper Floridan aquifer were obtained from reports by Ferguson and others (1947), Rosenau and others (1977), and Bush and Johnston (1988). Off-channel springs required assigning a constant volumetric flow rate to a node in the finite-element mesh located nearest to the spring (pl. 1). Nodal-discharge rates were adjusted from published values to estimate October 1986 springflow, because springflow was not measured for this study. Rates used in the calibrated Upper Floridan model total 332.6 Mgal/d and are listed in table 6. Off-channel springflow was held constant for all simulations because discharge measurements corresponding to the hypo-

Table 6. Calibrated spring discharge from Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin (from Torak and others, 1996)

Name	Node	Discharge (million gallons per day)
Chattahoochee Spring	2593	0.02
Glen Julia Springs	3110	.37
Indian Springs	2443	.45
White Spring	1634	1.22
Black Spring	1075	47.31
Double Spring	1075	24.24
Blue Spring	1751	92.75
Blue Hole Spring	1972	41.15
Bosel Spring	2046	52.37
Gadsden Spring	1074	11.63
Hays Spring	2497	14.96
Mill Pond Spring	1076	21.46
Sand Bag Spring	757	7.48
Springboard Spring	1145	11.25
Daniel Spring	2901	5.98
Total discharge		**332.64**

thetical hydrologic conditions represented in the simulation matrix (table 1) were not available. Consequently, off-channel springflow was assumed to be unaffected by simulated changes in stream stage and aquifer head.

Springs in Alabama and Georgia were represented as in-channel springs, such as Radium Springs in Dougherty County, Ga., which discharges directly to the Flint River. In-channel springflow was assumed to vary with changes in the aquifer head and stream stage of the reach containing the spring. Because the head-dependent boundary that simulates in-channel springs also simulates ground-water discharge to the corresponding stream reach, in-channel springflow and other discharge from the aquifer to the stream reach were inseparable as water-budget components. Thus, they appear in the water-budget tables as a single component (see tables 10–14). Also, for this reason, calibrated flow rates to in-channel springs could not be listed in table 6 in the same manner as for off-channel springs.

Hydraulic-Property Zones

Values for aquifer hydraulic conductivity and confining-bed vertical hydraulic conductance were input to MODFE by using hydraulic-property zones. These zones consist of a collection of finite elements (pl. 6); all elements of a zone contain identical values for hydraulic properties, and are the same as those established for the calibrated Upper Floridan and Intermediate models (Torak and others, 1996). Values of hydraulic conductivity used in the calibrated models are listed in table 7 by hydraulic-property zone; values of vertical hydraulic conductance for (linear) steady vertical leakage in the Intermediate model are listed in table 6. Variations in hydraulic conductivity of the Upper Floridan aquifer were determined from transmissivity and thickness data compiled in the Dougherty Plain by Hayes and others (1983) and Torak and others (1993), and from data on file at the USGS, District Office, Atlanta, Ga. Detailed zones of hydraulic conductivity in

Table 7. Calibrated hydraulic conductivity values by zone from Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin (from Torak and others, 1996)
[Zone numbers on plate 6; hydraulic conductivity in feet per day]

Upper Floridan model						Intermediate model		
Zone number	Number of elements	Hydraulic conductivity	Zone number	Number of elements	Hydraulic conductivity	Zone number	Number of elements	Hydraulic conductivity
1	149	1,350	27	873	130	1	73	20
2	53	2,100	28	15	2,000	2	1,165	25
3	53	1,800	29	8	9,000	3	163	10
4	13	1,200	30	10	10,500	4	144	20
5	2	1,200	31	196	200	5	866	40
6	8	600	32	683	900	6	416	60
7	4	720	33	397	1,344	7	1,165	20
8	715	1,100	34	1,857	1,300	8	15	60
9	12	5,500	35	47	500	9	17	20
10	11	9,500	36	623	1,700			
11	3	130	37	92	1,200			
12	81	750	38	15	1,500			
13	135	130	39	40	130			
14	606	1,600	40	92	1,500			
15	16	15,000	41	452	400			
16	20	4,000	42	545	600			
17	43	18,500	43	453	480			
18	88	250	44	679	1,300			
19	36	900	45	65	1,000			
20	167	8,000	46	201	280			
21	58	8,500	47	379	200			
22	65	350	48	252	500			
23	45	2,200	49	375	1,800			
24	818	2,700	50	554	1,600			
25	13	20,000	51	130	1,200			
26	36	1,150	52	12	0			

the Albany, Ga., area were defined by using data of the frequency and distribution of fractures and solution openings (see Torak and others, 1993, fig. 8). Variations in thickness and hydraulic conductivity of water-bearing units of the Intermediate system were obtained from data contained in reports by Schmidt (1978, 1979, 1984), and Schmidt and Coe (1978), Schmidt and Clark (1980), Schmidt and others (1980), and from aquifer-test results provided by Jeffry R. Wagner (formerly of Northwest Florida Water Management District, Havana, Fla., written commun., 1988).

Distribution of Ground-Water Withdrawal

The distribution of ground-water withdrawal in the study area was obtained from a compilation of pumpage records on file at the USGS District Office, Atlanta, Ga., and those obtained from various State offices within whose jurisdiction specific parts of the study area reside. As a follow-up to previous investigations, including the model study of the lower ACF River Basin (Torak and others, 1996), pumpage data were recompiled and state agencies were solicited for new data. However, no new information was available, therefore, the distribution and magnitude of pumpage for October 1986 used in the Upper Floridan model for this study is identical to that used in the previous study (Torak and others, 1996). A brief description of well

pumpage follows. The hydrologic consequences of using potentially incomplete pumpage information on model results and on study conclusions are discussed later in appropriate sections of this report.

The distribution of pumpage in Alabama and Florida for October 1986 was obtained from estimates of withdrawal and from water-use information, such as location and type of use (public supply, irrigation, domestic), reported incidentally with water-level and hydrogeologic data. Average pumping rates were assigned to each water use type at the well locations to give estimates of pumpage. Actual pumping rates were used for wells that had this information documented for October 1986.

Locations and pumping rates of wells in Georgia for October 1986 were obtained from several sources; data on file at the USGS, District Office, Atlanta, Ga.; pumpage reports from the State of Georgia Irrigation Reporting System (GIRS); State Irrigation Well Survey of 1980; miscellaneous files; and communication with water managers, such as county-extension agents of the U.S. Department of Agriculture. Information obtained from these sources were used to update the 1980 data to those for 1986 conditions. Pumpage records from the GIRS were used to establish a trend in agricultural pumpage during the irrigation growing season, which begins in March and extends through October. These records indicated that irrigation pumpage during October 1986 was about one-fifth of the rates that typically are reported during the height of the growing season, which is late spring to early summer. However, because a variety of sources for pumpage information was consulted, pumpage estimates for October 1986 are higher than estimates derived from any one source of data, such as from the GIRS, which contained incomplete information.

The seasonal-pumpage trend that was established by the GIRS was applied to all irrigation wells tapping the Upper Floridan aquifer in the study area, including part of the study area in Florida, to obtain a pumping rate representative of October 1986 conditions. That is, all irrigation wells were assumed to be pumping at one-fifth of the maximum growing-season rates at some instant in time during October 1986. Because neither the GIRS nor other pumpage records obtained by the sources indicated above could establish, specifically, which wells were pumping during October 1986, it was assumed that all irrigation wells were pumping simultaneously at the reduced rate. Maximum growing-season pumping rates for irrigation totaled about 2.2 billion gallons a day; hence, the October 1986 pumping rate used in the Upper Floridan model was about 432.5 Mgal/d. Municipal and industrial pumpage for October 1986 totaled about 42.5 Mgal/d. This is not to say that the irrigation pumping rate was maintained all day, every day, throughout the month. However, owing to the linearity of the flow system, as demonstrated by previous simulations by Torak and others (1996), and the steady-state simulation approach, one pumping rate was required for simulating October 1986 conditions, and the rates established on the basis of seasonal-pumpage trends, given by GIRS records, provided a scientific rationale for the pumpage used in the calibrated model. That this approach provided a viable estimate of an October 1986 pumping rate is supported further in the following discussion. Later sections of this report describe the hydrologic implications of a linear flow system, and of any nonsteady-state, flow-system response (time lag), with regard to pumpage change.

Maximum growing-season pumpage of about 2.2 billion gallons a day, obtained by the procedure described above, is a reasonable and consistent estimate of ground-water withdrawal during a growing season, when compared with estimates of pumpage used in a previous model study of the Dougherty Plain by Hayes and others (1983). Hayes and others (1983) used results of a field survey of existing irrigation systems in the spring of 1980 to obtain an annualized rate of agricultural ground-water pumpage of about 1,100 ft^3/s, or about 711 Mgal/d (p. 75 and fig. 37 of Hayes and others, 1983). When applied at a constant rate to an assumed irrigation growing season of 107 days (June 1 to September 15), as was done in their study, the growing season rate for 1980 was about 3.4 times larger than the annualized rate (365 days divided by 107 days equals 3.41), or about 2.4 billion gallons a day. However, GIRS records indicate that maximum pumpage occurs during July and August at about twice the rate as in June and September. Factoring this temporal variability into the pumping-rate computation yields a maximum pumping rate during the growing season of about 3 billion gallons a day in 1980.

The maximum pumping rate of 2.2 billion gallons a day used in the present study as a basis for computing agricultural pumpage in October 1986 also is reasonable and consistent when compared with recent

trends in ground-water use. Agricultural pumpage in October 1986, as estimated for this study and for the previous study by Torak and others (1996), represents a 28 percent reduction from pumpage in 1980. This reduction is consistent with the reduction in agricultural water-use estimates for ground water in the Chattahoochee and Flint River basins over the same time period, as reported by Marella and others (1993). They indicate a 29 percent reduction in ground-water use for agriculture, from an annualized rate of 241.13 Mgal/d in 1980, to 171.59 Mgal/d in 1985 (table 19, Marella and others, 1993).

Wells were represented in the Upper Floridan model as point withdrawal at nodes in the finite-element mesh. Well pumpage was distributed from its actual location in the basin to nearest nodes in the mesh. Element sizes in the mesh allowed most well pumpage to be represented at nodes that were within 2,000 ft of actual well locations. The manner in which wells were represented in the Upper Floridan model is identical to that used in the calibrated, steady-state model developed for this study area by Torak and others (1996). Thus, there were 1,380 nodes used in the Upper Floridan model to simulate well pumpage (pl. 7), excluding 14 nodes where springflow was simulated (shown on plate 1).

Ground-water pumpage in the Intermediate system in Florida is considered negligible and was not simulated in the Intermediate model. The Intermediate system functions as a secondary aquifer (the Upper Floridan aquifer is the primary source of ground water) and, because of the rural nature of this part of the lower ACF River Basin, the number of domestic ground-water supply wells tapping the Intermediate system, and hence, withdrawal from the aquifer, is negligible (Jeffry R. Wagner, formerly of Northwest Florida Water Management District, Havana, Fla., written commun., 1988).

Calibration to October 1986 Conditions

Acceptance of the Upper Floridan and Intermediate models as reliable representation of flow-system response to hydrologic stress is contingent upon favorable comparison of model results with observations made about the system during historic conditions. Because system response to stress during low-flow, low-water-level conditions in the aquifer-stream-reservoir system in late October 1986 was of primary concern to the study, computer models were constructed to simulate these conditions. Model accuracy was measured by the ability of the Upper Floridan and Intermediate models to simulate observed ground-water levels and stream-aquifer flows within acceptable levels of computational error. The process by which values of hydraulic properties were adjusted in the models, within plausible limits, to achieve acceptable comparisons of simulation results with observed hydrologic phenomena is termed calibration.

The Upper Floridan and Intermediate models were calibrated successfully to steady-state, October 1986 conditions in a previous study by Torak and others (1996). The procedure used to calibrate the Upper Floridan and Intermediate models involved trial-and-error adjustments to hydraulic properties, which served as model inputs, and interpretation of resultant changes in ground-water levels and stream-aquifer flows. Comparisons of computed and measured values at discrete points (wells and surface-water-measurement sites) were quantified to give an indication of progress toward achieving calibration during the procedure. Brief descriptions of processes and results used to achieve calibration are contained below; details of the calibration procedure are given in Torak and others (1996).

Pumping rates of wells were not adjusted during calibration; however, effects of changing pumping rates on computed water levels and on stream-aquifer flows were determined in a sensitivity analysis that was performed using the calibrated Upper Floridan model by Torak and others (1996). Simulations involving simultaneous changes to well-pumping rates and boundary conditions were performed in this study by using the Upper Floridan model to determine the effect these changes have on other flow-system components.

Ground-Water-Level Residuals

Ground-water-level residuals, that is, simulated minus observed water levels, were required to satisfy an acceptance criterion of 7 ft. This criterion was established on the basis of inaccuracies in water-level mea-

surements that were attributed to imprecise land-surface altitude at wells, and uncertainty in using a general flow-system characterization to represent parts of the study area that require more detail. Thus, computed water levels were not expected to be more accurate than the accuracy of water levels and the level of detail in the hydrologic characterization. Average ground-water-level residuals were expressed as the root-mean-square error of residuals[1] for comparison with observed values during calibration. Values of root-mean-square error of residuals that satisfied the acceptability criterion were computed as 7 ft and 4.4 ft, respectively, for the Upper Floridan and Intermediate models. Lists of computed and measured ground-water levels and ground-water-level residuals for both models are given in the appendix.

Ground-water-level residuals were classified in a histogram (fig. 20) and plotted on a map of the study area (pl. 8) to evaluate normality and spatial randomness in model error. These illustrations show that ground-water-level residuals for the calibrated models are normally distributed around an arithmetic mean near zero (0.4 and minus 0.6, respectively, for Upper Floridan and Intermediate models; see tables in appendix) and that most residuals are distributed randomly over the study area. Both the near zero mean and random distribution of residuals are desirable attributes of calibrated models.

Plots of three statistics, root-mean-square error of residuals, sum-of-residuals squared, and standard deviation of residuals (fig. 21) were made by using computed and observed ground-water levels, following changes to model inputs and subsequent simulation. These plots show the net gain in model accuracy as calibration was achieved and the somewhat subjective nature of deciding when to terminate the procedure after additional changes to model inputs yield only marginal, statistical improvements to computed ground-water levels. Statistics for water-level residuals that summarize the calibration process are listed in table 8.

Computed Stream-Aquifer Flows

The ability of the models to evaluate ground-water and surface-water relations is determined by comparing flows across streambeds, termed stream-aquifer flows, computed by the models with flows that are derived from actual streamflow measurements. Stream-aquifer flow for a specific reach is not streamflow; rather, it is the flow of water across the streambed that either increases or reduces streamflow. Positive stream-aquifer flow indicates that the stream, or stream reach, has gained flow from ground water entering the channel across the streambed (gaining stream). Negative stream-aquifer flow indicates that streamflow is lost to the aquifer by leaking out of the channel across the streambed, thus recharging the aquifer (losing stream). Neither positive nor negative stream-aquifer flow can be determined simply by taking one streamflow measurement; upstream and downstream measurements for a reach are necessary, and the values are subtracted to obtain stream-aquifer flow.

Errors contained in ground- and surface-water data affect the ability of the models to be calibrated to precise values of stream-aquifer flow. Uncertainties surrounding streamflow measurements indicate that ‘measured’ stream-aquifer flows contain errors, which vary in magnitude by reach. Compounding these errors is the use of a range of acceptable ground-water levels in stream-aquifer-flow computations involving the models. Therefore, individual acceptance criteria were established for each of the 37 reaches for which upstream and downstream flow measurements were available (pl. 9) for comparison with computed stream-aquifer flows provided by the models. These criteria incorporate errors associated with streamflow measure-

[1] Root-mean-square error of residuals is computer as

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_c - h_{obs}\right)_i^2}$$

where h_c is computed head, h_{obs} is observed head, n is the number of pairs of h_c and h_{obs}, equal to 19 for the Intermediate model and 284 for the Upper Floridan model.

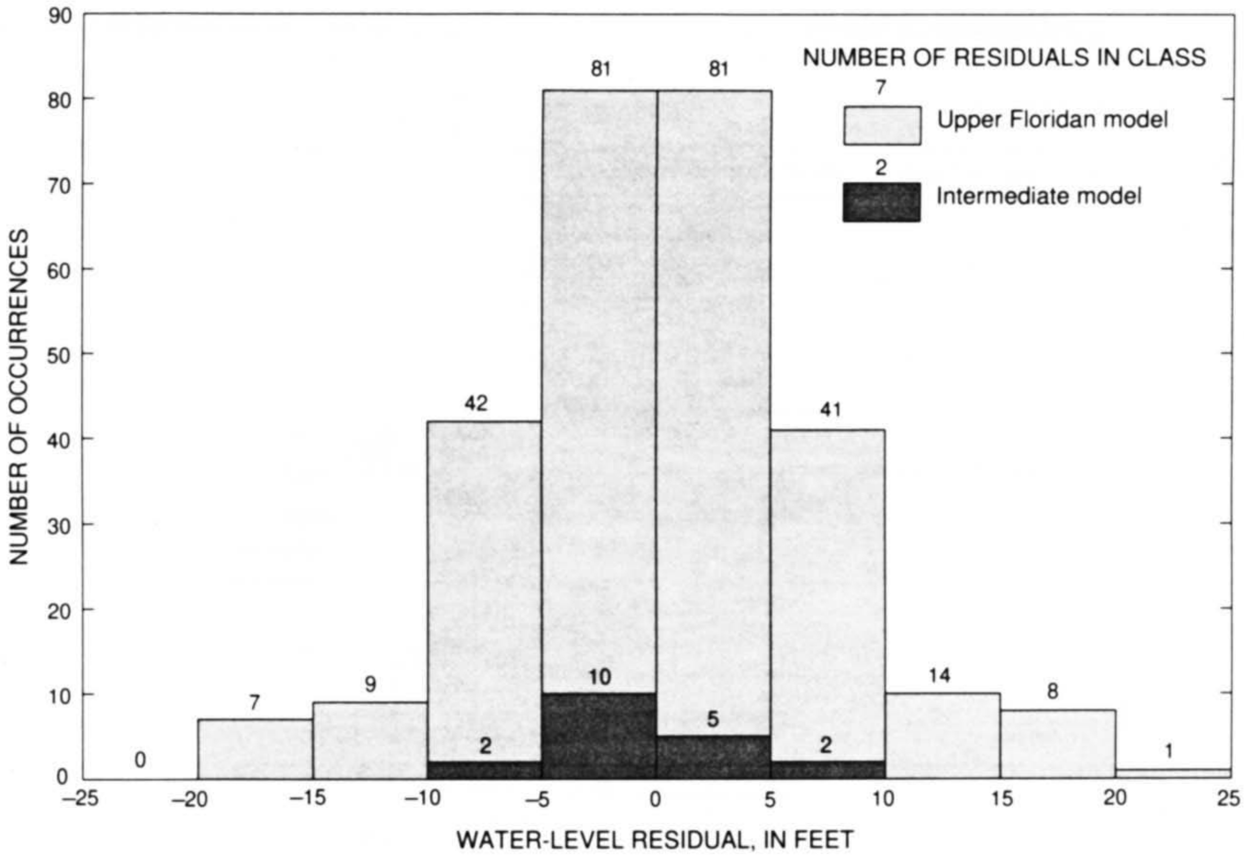

Figure 20. Frequency of ground-water-level residuals from model calibration (from Torak and others, 1996).

ments, computed ground-water levels, and the calculation of average streamflows into target ranges of flows that are established and satisfied by reach as a requirement for calibration, instead of comparing one "measured" stream-aquifer flow to one computed value.

Computed stream-aquifer flows resided within the corresponding target-ranges for 27 of 37 reaches (table 9), thus meeting this acceptance criterion for calibration. Errors in computed flow were expressed in terms of total streamflow and magnitude of stream-aquifer flow (EQ and EqeTOT terms, respectively, in table 9). These errors do not seem to be systematic; neither accumulating in the downstream direction for adjacent reaches nor increasing with increased magnitude of flow values.

Simulated Potentiometric Surfaces

Simulated potentiometric surfaces for October 1986 conditions in the Upper Floridan aquifer and water-bearing units of the Intermediate system, simulations R1P1 and R1POCT, respectively, of tables 1 and 2, were obtained from the calibrated models of Torak and others (1996), and indicate reasonable agreement with ground-water-level measurements (pl. 10). Contours depicting the simulated potentiometric surface agree well with ground-water-level measurements shown as point values. Acceptance of the simulated potentiometric surfaces was made indirectly in Torak and others (1996) as calibration efforts focused primarily on meeting the established criteria for ground-water-level residuals and stream-aquifer flows. Thus, comparison of computed ground-water levels with measured values adds a post script to the calibration procedure and its successful accomplishment, and is used to qualitatively evaluate goodness of fit and reliability of the models to represent historic hydrologic conditions. A detailed comparison of computed and measured ground-water levels for the calibrated models is given in Torak and others (1996), and is not repeated here. Inasmuch as the present study builds on results of the calibrated Upper Floridan and Intermediate models derived from the

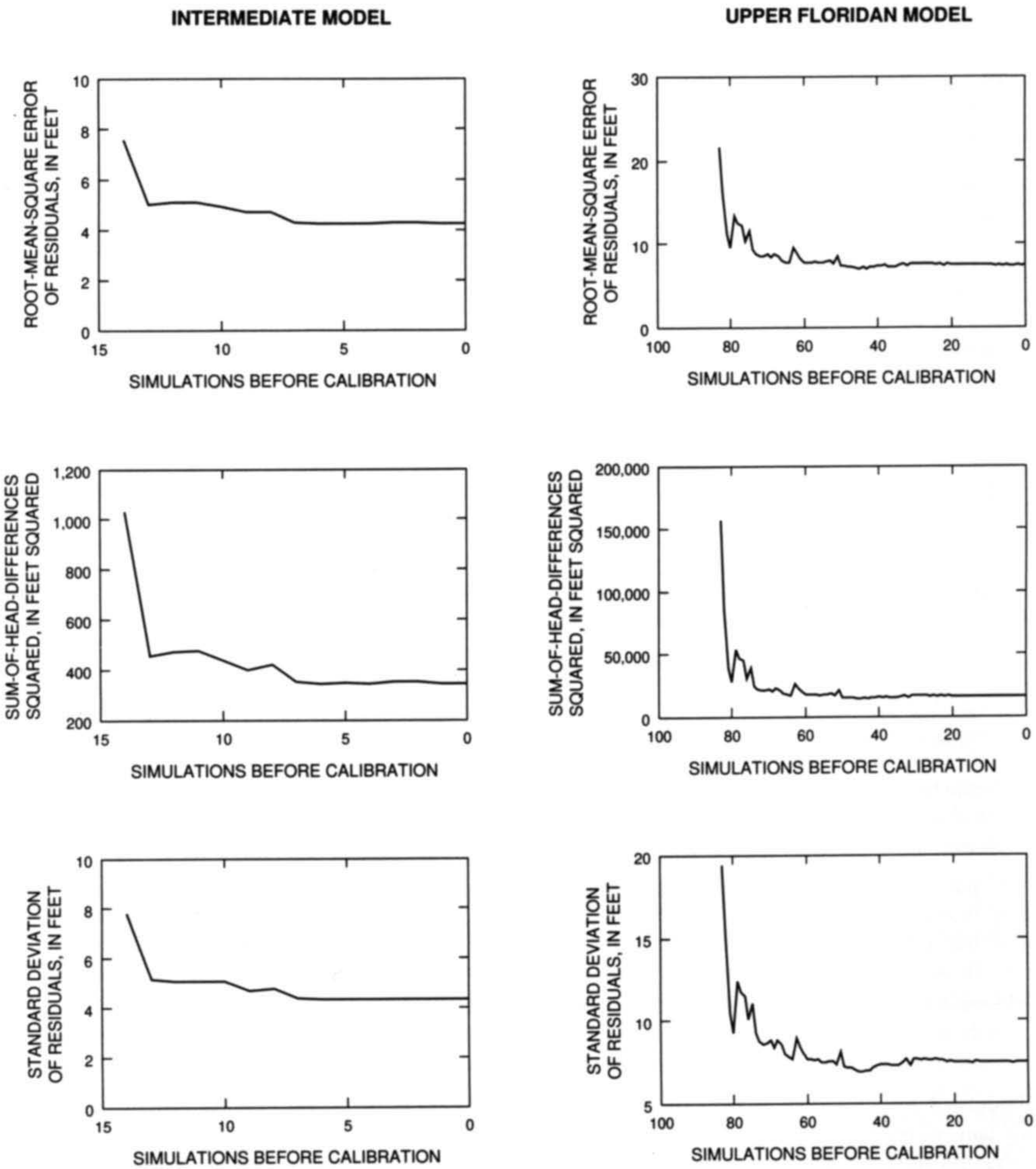

Figure 21. Root-mean-square residual, sum-of-head-differences squared, and standard deviation of ground-water-level residuals by simulation during calibration of Intermediate and Upper Floridan models (from Torak and others, 1996).

previous study, computed ground-water levels are presented in map form as a reference for subsequent simulation results and discussions. The discontinuity in simulated surfaces at the boundary between the models is a result of portraying surfaces for two vertically discontinuous units, the Upper Floridan aquifer and Intermediate system, on the same illustration (pl. 10).

Table 8. Statistics for ground-water-level residuals from the calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin (from Torak and others, 1996)

[ft^2, feet squared; ft, feet; RMSE, root-mean-square error of residuals]

	Upper Floridan model	Intermediate model
Number of terms	284	19
Sum of squares, ft^2	13,728	360
RMSE, ft	6.95	4.35
Standard deviation, ft	6.95	4.43
Average residual, ft	0.40	-0.59
Percentage of residuals within:		
1 standard deviation	70.1	63.2
2 standard deviations	93.3	94.7
3 standard deviations	100	100

Number of water-level residuals between:

Class interval (feet)	Number of occurrences	Number of occurrences
-25 to -20	0	0
-20 to -15	7	0
-15 to -10	9	0
-10 to -5	42	2
-5 to 0	81	10
0 to 5	81	5
5 to 10	41	2
10 to 15	14	0
15 to 20	8	0
20 to 25	1	0

Directions of Ground-Water Movement

Directions of ground-water movement in the Upper Floridan aquifer and Intermediate system can be inferred from contours of simulated potentiometric surfaces obtained from calibrated models developed by Torak and others (1996), and shown on plate 10. These surfaces indicate that ground water moves in these units as described in the conceptualization of the flow system. Movement of ground water within the study area is controlled by regional inflow from outcrop areas, parts of the Solution Escarpment (eastern boundary), and ground-water divides (western boundary), and by regional outflow across remaining parts of the eastern (Solution Escarpment) and southern boundaries, and discharge to surface-water features and swamps. In the Upper Floridan model, ground water flows into the northern and central parts of the lower ACF River Basin from outcrop areas along the northern model boundary and from regional flow across the eastern and western model boundaries. Ground water discharges from the Upper Floridan aquifer along surface-water features, primarily the Apalachicola, Chattahoochee, and Flint Rivers, and along parts of the eastern and southern model boundaries as regional flow. In the Intermediate model, ground water enters the study area across the northern model boundary at the outcrop of the Intermediate system, northern part of the western boundary, and southern part of the eastern boundary, and flows out of these units by upward vertical leakage

Table 9. Stream-aquifer flows from the calibrated Upper Floridan and Intermediate models of the lower Apalachicola-Chattahoochee-Flint River Basin (from Torak and others, 1996)

[Reach numbers shown on plate 9; streamflow, average flux, target range, and computed flux, in cubic feet per second]

Reach number	Stream	Streamflow, Q	Average flux[1], qe_i	Target range		Computed flux[4], qc_i	Errors, in percent	
				Fluxmin[2]	Fluxmax[3]		EQ[5]	EqeTOT[6]
[7]1	Gum Creek	5.5	10.9	9.8	12	3.6	–133	0.2
[7]2	Cedar Creek	.7	1.3	1.2	1.4	1.3	0	0
[7]3	Swift Creek	4.6	9.2	8.3	10.1	3.8	–117	.1
[7]4	Jones Creek	1.2	2.3	2.1	2.5	2.3	0	0
[7]5	Abrams Creek	4.6	9.1	8.2	10	2.6	–141	.2
[7]6	Mill Creek	6	11.9	10.7	13.1	6.9	83.3	.1
7	Cooleewahee Creek	.3	.5	.5	.6	.5	0	0
8	Chickasawhatchee Creek	12.2	4.2	1.8	6.6	4.1	–0.8	<.1
[7]9	Chickasawhatchee Creek	7.2	–14.3	–15.7	–12.9	.3	203	.3
[7]10	Chickasawhatchee Creek	1.3	2.5	2.3	2.8	2.8	23.1	<.1
11	Dry Creek (Ga.)	4.3	–1.6	–2.4	–.7	2.8	102	.1
[7]12	Spring Creek	.8	1.5	1.4	1.7	3.5	250	<.1
13	Spring Creek	9.2	15.4	13.6	17.2	19.5	44.6	.1
14	Spring Creek	14.8	–4.2	–7.2	–1.2	1.1	35.8	.1
[7]15	Sawhatchee Creek	4.9	9.7	8.8	10.7	9.6	–2.0	<.1
[7]16	Cowarts Creek	9.4	18.7	16.8	20.6	19.9	12.8	<.1
[7]17	Marshall Creek	16.4	32.7	29.4	36.	31.6	–6.7	<.1
18	Spring Creek	36.3	47.2	39.9	54.5	42.2	–13.8	.1
[7]19	Dry Creek (Fla.)	44.3	88.6	79.7	97.5	42.1	–105	1.1
20	Ichawaynochaway Creek	162	83	50.7	115	52.6	–18.8	.7
21	Ichawaynochaway Creek	203	0	–40.6	40.6	23.7	11.7	.6
22	Muckalee Creek	91.7	16.7	1.6	35	17.8	1.2	<.1
23	Muckalee Creek	98	–4.0	–23.6	15.6	3.9	8.1	.2
24	Muckalee Creek	106	19	–2.1	40.1	14.2	–4.5	.1
25	Kinchafoonee Creek	157	–12	–43.4	19.4	–2.3	6.2	.2
26	Kinchafoonee	154	5.0	–25.7	35.7	5.9	.6	<.1
27	Chipola River	115	114	91.1	137	115	.5	<.1
28	Chipola River	344	343	309	377	340	–1.0	.1
29	Chipola River	344	343	309	377	359	4.7	.4
30	Flint River	795	–49	–129	30.5	6.3	7.0	1.3
31	Flint River	1,256	549	424	675	604	4.4	1.3
32	Flint River	1,795	530	351	710	537	.4	.2
33	Flint River	2,140	160	–54	374	364	9.5	4.8
34	Flint River	2,400	360	120	600	352	–.3	.2
35	Apalachicola River	6,042	127	–477	731	282	2.6	3.7
36	Apalachicola River	6,219	227	–395	849	166	–1.0	1.5
37	Apalachicola River	6,829	994	311	1,677	523	–6.9	11.2
	Total		**4,222**			**3,963**		

$$^{1}qe_i = \frac{Fluxmin + Fluxmax}{2}, i = 1, 37.$$

[2]Fluxmin = $(Q_d - EF \times Q_d) - (Q_u + EF \times Q_u)$, ft^3/s.

[3]Fluxmax = $(Q_d - EF \times Q_d) - (Q_u - EF \times Q_u)$, ft^3/s. Q_u and Q_d are streamflows at the upstream and downstream ends of a reach, respectively, and EF is an error factor equal to 0.1 reaches 1–27 and 0.05 for reaches 28–37.

$$^{4}qc_i = \alpha L(h_B - h);\ \alpha = \frac{K_r W_r}{b_r},$$

for reach, where estimates are used to define average streambed hydraulic conductivity (K_r), width (W_r), and thickness of streambed sediments (b_r); stream state (h_B) and aquifer head (h) obtained from calibrated models; length of reach (L) computed from finite-element mesh.

$$^{5}EQ = \frac{qc_i - qe_i}{Q} \times 100, percent,\ i = 1, 37.$$

$$^{6}EqeTOT = \frac{qc_i - qe_i}{Total, qc_i} \times 100,\ percent,\ i = 1, 37.$$

[7]Reach originates within study area or discharge at one end of reach equals zero.

to the Chipola River and Apalachicola River and flood plain, and by regional flow across the southern model boundary, which is located in Apalachicola Bay.

The general pattern of regional ground-water flow in the Upper Floridan aquifer and Intermediate system, shown on plate 10, is altered in some areas by a combination of hydrologic influences causing local irregularities in the flow system. These irregularities are manifested in irregularly spaced contours of the potentiometric surfaces and in contours that change direction over short distances. Nonhomogeneity of hydraulic properties of aquifers and overlying sediments, spatial variation in vertical leakage from semiconfining units, and stress due to pumpage all work in varying degrees throughout the study area to alter regional ground-water flow on a local scale. In some areas, such as east of Lake Worth, near Albany, Ga., closely spaced contours indicate relatively steep hydraulic gradients, which are believed to be caused by zones of low hydraulic conductivity situated among higher hydraulic conductivity zones. Areas where contours are widely spaced, such as in the vicinity of Lake Seminole, indicate relatively flat hydraulic gradients, although ground-water flow can be quite large if hydraulic conductivity is high and the aquifer is thick. Aquifer nonhomogeneity coupled with variations in recharge by vertical leakage and in pumpage creates a region of diverging flow in the area east of Albany, Ga., near Sylvester, Ga., where pronounced bending of the 220-ft potentiometric contour is seen on plate 10.

Hydrologic stress such as pumpage and springflow seem to have an aggregate rather than an individual effect on the potentiometric surface of the Upper Floridan aquifer, causing an overall lowering of water levels with little evidence of distinct drawdown patterns (cones of depression) or alteration of the regional ground-water-flow regime. An exception is near Port St. Joe, Fla., where pumpage from the Upper Floridan aquifer not only creates a distinct drawdown pattern in the pumped aquifer, but also causes a similar pattern in the potentiometric surface of the overlying Intermediate system. Aside from this local, pumpage-induced irregularity, the effects of hydrologic stress on creating distinct drawdown patterns in the potentiometric surface of the aquifers are minimal.

Surface-water features affect directions of ground-water movement in the well-drained, highly transmissive parts of the Upper Floridan aquifer. In the area between Albany and Newton, Ga., near-conduit-flow conditions enable ground water to move easily toward the Flint River, and high horizontal ground-water flow and gentle hydraulic gradients typically exist (Hicks and others, 1987; Torak and others, 1993). In other areas, ground-water flow from the aquifer to rivers is indicated by closely spaced contours of the potentiometric surface that bend sharply upstream at the river, such as immediately north of Bainbridge, Ga., and along the Chattahoochee and Apalachicola Rivers.

The influence of vertical leakage from the overlying semiconfining unit on directions of ground-water movement in the Upper Floridan aquifer is inferred from a comparison of the potentiometric surface (pl. 10) with a plot of water-level differences between the aquifer and undifferentiated overburden (pl. 11). Contours of the potentiometric surface indicate high water level and diverging ground-water flow in an area about 5 mi southeast of the Dougherty-Worth County line near Gordy, Ga. This area also contains higher land-surface altitude and greater thickness of undifferentiated overburden than surrounding areas; hence, it constitutes an ground-water-recharge area, as indicated by water-level differences on plate 11. A similar pattern in the potentiometric surface occurs about 4 mi north of the Dougherty-Lee County line between the Flint River and Muckalee Creek. This is an interstream area containing higher land-surface altitude than surrounding areas and several small ponds, indicating a shallow depth to the water table, thus a high potential for water in the semiconfining unit to recharge the Upper Floridan aquifer.

Throughout most of the lower ACF River Basin, ground water moves vertically downward to recharge the aquifers from overlying semiconfining units consisting of undifferentiated overburden and terrace and undifferentiated (surficial) deposits. Upward vertical movement exists only in the vicinity of stream channels, lakes and swamps (pl. 11; fig. 22). Springflow may reverse areal patterns of downward leakage on a local scale too small to depict on the illustrations. This apparent leakage incongruity exists because some springs

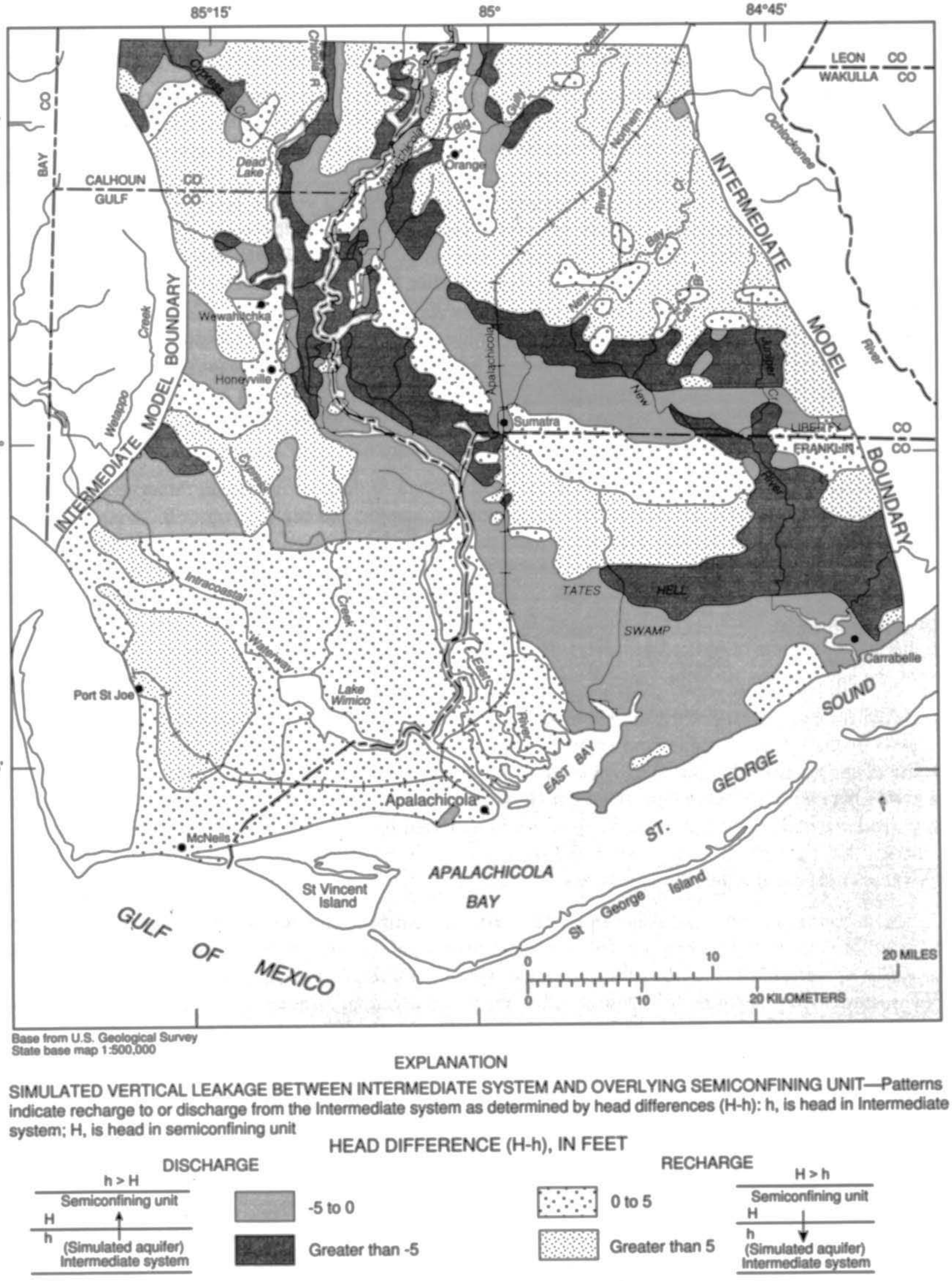

Figure 22. Simulated vertical leakage between the Intermediate system and overlying semiconfining unit (modified from Torak and others, 1996).

represent isolated point-discharge features that might be situated within larger areas of ground-water recharge. Exceptions to these general patterns of vertical ground-water movement occur along the Brothers and Apalachicola Rivers, downstream of Sumatra, Fla., where movement of ground water seems to be vertically downward from surficial deposits in the Intermediate system. Another exception exists in southern and eastern Franklin County, Fla., where upward vertical leakage from the Intermediate system recharges surficial deposits beneath Tates Hell Swamp. Lake Seminole functions as a recharge and discharge mechanism to the Upper Floridan aquifer, accepting ground-water discharge in the northern part of the lake, and providing ground-water recharge in the southern part (pl. 11).

Diverse vertical ground-water movement was simulated in the Intermediate model and is indicated by head differences between the Intermediate system and underlying Upper Floridan aquifer (fig. 23). Upward vertical leakage (recharge) from the Upper Floridan aquifer to the Intermediate system exists along the Apalachicola, Chipola, and New Rivers, between Wilma and Sumatra, Fla. (Liberty and Franklin Counties, Fla.), and in Tates Hell Swamp along the Gulf coast in southern Franklin County. Downward leakage (ground-water discharge) from the Intermediate system to the Upper Floridan aquifer exists in the northern and western parts of the Intermediate model, with the exception of the flood-plain area of the Apalachicola River and three small areas in central Gulf County near Wewhahitchka, Honeyville, and Overstreet, Fla.

Directions of vertical leakage indicate flow-through movement of ground water into and out of the Intermediate system in specific areas of Gulf and Franklin Counties, Fla. (figs. 22, 23). In eastern Gulf County, pumpage in the Upper Floridan aquifer at Port St. Joe, Fla., is partly responsible for inducing vertical downward leakage from the overlying semiconfining unit, through the Intermediate system, and into the underlying pumped aquifer. In part of Tates Hell Swamp, northern Franklin County, ground water in the surficial deposits recharges the Intermediate system which, in turn, discharges water to the underlying Upper Floridan aquifer. The absence of pumpage here makes this flow-through leakage seem to be a natural movement of ground water, with the Swamp recharging the underlying units. South of this location, flow-through-vertical movement of ground water is reversed as upward flow from the Upper Floridan aquifer recharges the Intermediate system which, in turn, discharges water upward to surficial deposits and the Swamp. Vertical-flow directions are reversed again in a small area along St. George Sound, west of Carrabelle, Fla.

Surface-Water Influence on Ground-Water Flow

Ground-water flow in the lower ACF River Basin is influenced strongly by natural or man-made surface-water features. As evidenced by the sharp bending of simulated potentiometric contours (pl. 10), ground-water-flow directions for October 1986 were controlled primarily by the Flint River, Lake Seminole, and the Apalachicola, Chattahoochee, and Chipola Rivers. This influence was quantified in the digital models by computing stream-aquifer flow for simulations that varied stream stage and boundary conditions to the Upper Floridan aquifer and Intermediate system.

The Flint and Chattahoochee Rivers drain the Upper Floridan aquifer and undifferentiated overburden of regional inflow from the northwest and northeast. Potentiometric contours (pl. 10) bend upstream to create a regional-flow regime characterized by ground water discharge to the Flint and Chattahoochee Rivers. This pattern of regional ground-water discharge to the Flint and Chattahoochee Rivers is present in the lower ACF River Basin along the entire course of these rivers.

Functioning as a recharge and discharge mechanism for ground water, Lake Seminole is located within a broad, flat region in the potentiometric surface of the Upper Floridan aquifer at the confluence of Spring Creek and the Chattahoochee and Flint Rivers. The aquifer in this region is characterized by relatively small hydraulic gradients (pl. 10), but, as described previously, large amounts of ground-water movement is possible due to relatively high aquifer transmissivity. Potentiometric contours bend sharply upstream in the vicinity of the Lake indicating ground-water discharge to the rivers.

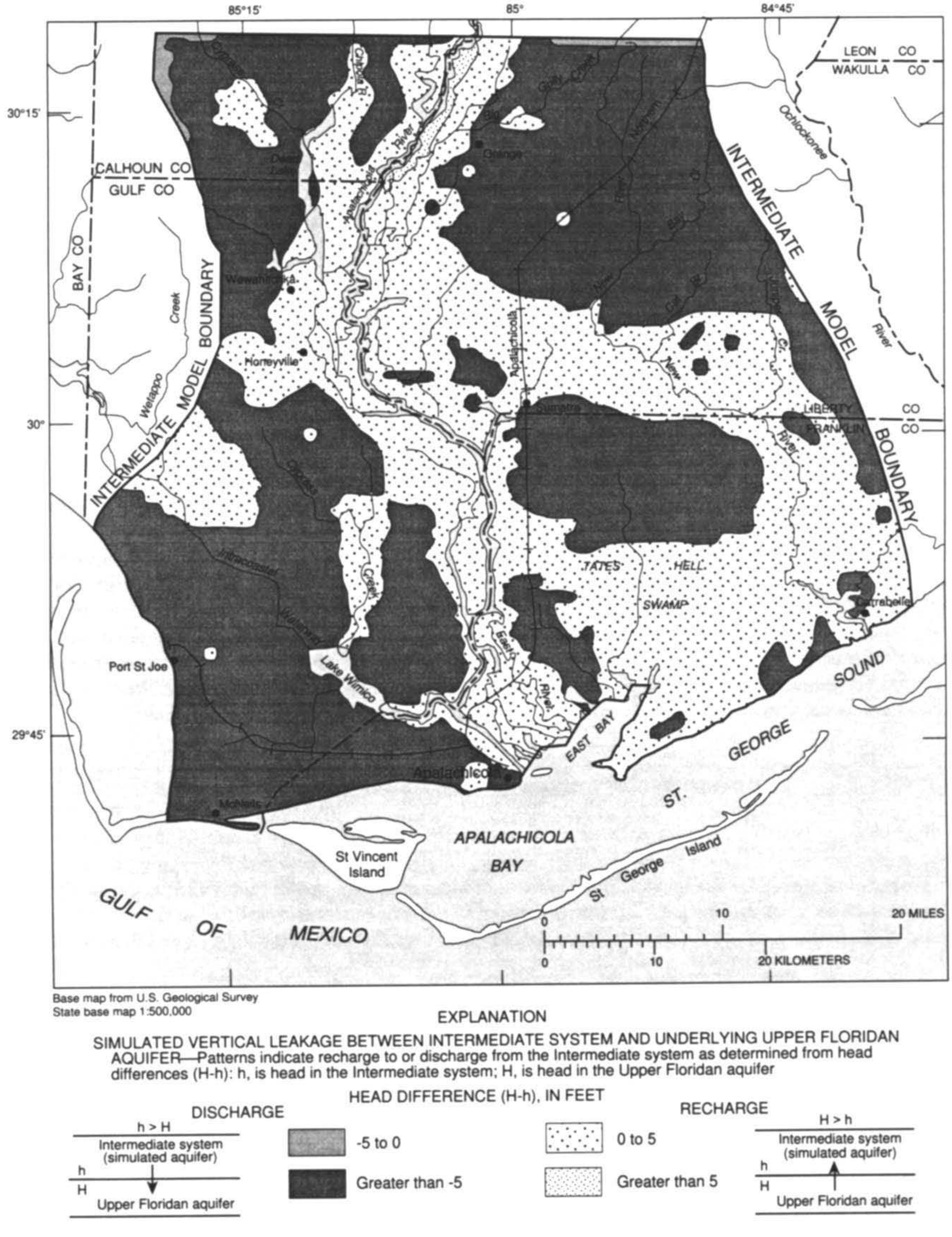

Figure 23. Simulated vertical leakage between the Intermediate system and underlying Upper Floridan aquifer (modified from Torak and others).

Two hydraulic factors contribute to producing less stream-aquifer flow downstream of Lake Seminole than upstream. First, the outcrop area of the Upper Floridan aquifer in Houston County, Ala., which is drained by the Chipola River and its tributaries, is not as extensive as the area drained by the Flint and Chattahoochee Rivers, Spring Creek, and their tributaries. Drainage of ground water by the surface-water system upstream of Lake Seminole reduces hydraulic potential, or head, in the aquifer, thus reducing gradients and flow to rivers that are located downstream of the Lake and far from the ground-water source (outcrop area). Second, variations in land-surface altitudes along the outcrop of the Upper Floridan aquifer cause ground-water levels in the relatively small area drained by the Chipola River and its tributaries to be 80 to 100 ft lower than levels that contribute flow to the Flint River. The reduced hydraulic potential caused by the lower altitude of the outcrop area drained by the Chipola River than outcrop areas drained by the Flint River, and to a lesser extent the Chattahoochee River, translates to low hydraulic gradients to drive stream-aquifer flow from the aquifer to the stream. Consequently, there is less stream-aquifer flow from rivers located downstream of Lake Seminole than upstream.

Approximately 8 mi downstream of Blountstown, Fla., the Apalachicola and Chipola Rivers begin to drain outcrop areas of the southward-dipping Intermediate system. A high degree of hydraulic connection between the Intermediate system and these surface-water features is indicated by sharp-upstream bending of contours of the simulated potentiometric surface at the rivers (pl. 10). However, the relatively short distance and low topographic relief between outcrop areas and rivers in comparison with the Upper Floridan aquifer cause the Intermediate system to be drained within a short distance downstream of the outcrop area. Most of the hydraulic potential for ground-water flow (hydraulic head) and stream-aquifer flow has dissipated from the Intermediate system within 30 mi of the outcrop area. As a result, the potentiometric surface in the region located south of Sumatra, Fla., within the southern half of Franklin and Gulf Counties, is broad and flat, nearly identical to river stage, and generally less than 10 ft above sea level.

The influence of small creeks and other surface-water features on the ground-water-flow system of the Upper Floridan aquifer and Intermediate system seems to be less than the influence of the Apalachicola, Chattahoochee, Chipola, and Flint Rivers and Lake Seminole. East of the Flint River, small creeks and streams drain the Solution Escarpment and exhibit a better hydraulic connection to the undifferentiated overburden than to the Upper Floridan aquifer (Hicks and others, 1987). Similar conditions exist west of the Chipola River in Jackson County near Marianna, Fla., and in Houston County near Dothan, Ala., where surface-water features drain thick overburden deposits along ground-water and river-basin divides that form the western study-area boundary. In this area, ground-water flow is influenced by springs, as they provide ground-water discharge to some creeks and streams.

Water-Budget Analysis

Water budgets were prepared on the basis of simulated inflows and outflows to the Upper Floridan and Intermediate models to provide a quantitative assessment of hydrologic components assumed to control ground water entering and exiting the study area, and to determine the effects of pumpage and hydrologic boundaries on the aquifer-stream-reservoir system. Simulated hydrologic conditions of dry and normal levels for boundary and semiconfining-unit head, 3 levels of stream stage, October 1986, Q_{90}[2], and Q_{50}[3], and ground-water pumpage at 5 multiples of October 1986 rates, including zero pumpage (table 1), were used to determine the importance of each water-budget component to the ground-water resources of the Upper Floridan aquifer and lower ACF River Basin. The lack of noticeable pumpage in the Intermediate system limited the water-budget analysis to an evaluation based on simulations in which only boundary and semiconfining-unit head and stream stage were changed, as listed in table 2.

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[2]Q_{90} is streamflow that is exceeded 90 percent of the time.

[3]Q_{50} is streamflow that is exceeded 90 percent of the time.

Zero-Pumpage Conditions

Simulations of zero pumpage were used as a reference to analyze changes to the flow system in terms of changes to water-budget components other than pumpage. For the Intermediate model, only simulations involving changes to lateral and vertical boundary conditions and stream stage were performed; thus, zero-pumpage scenarios were the extent of the water-budget analysis for the Intermediate system. However, for the Upper Floridan model, zero pumpage was simulated to provide hydrologic-reference conditions for subsequent simulations that tested flow-system response to changes in boundary conditions and stream stage other than pumpage. Besides comparisons of water-budget components based on simulations in which only pumping rates were changed, comparison of water-budget components derived from the 6, zero-pumpage scenarios themselves enabled analyses to be made of flow-system response to only boundary conditions and stream stage, without any hydrologic implications caused by pumped wells. Hence, comparisons of water-budget components resulting from simulations involving either individual or collective changes to boundary conditions, stream stage, and pumpage permitted a thorough evaluation to be made of ground-water resources and flow-system response to various hydrologic conditions. Furthermore, the zero-pumpage simulations in the Upper Floridan and Intermediate models might represent hydrologic conditions that existed at one time in the lower ACF River Basin before pumpage began. Although notable pumpage in the Upper Floridan aquifer postdates completion of surface-water-control structures, such as Jim Woodruff Lock and Dam and the Flint River Dam, which also influence flow and water resources in the aquifer-stream-reservoir system, the advent of notable pumpage to the Intermediate system has yet to be realized.

Upper Floridan Model

Computed volumetric flow rates for water-budget components of the Upper Floridan model derived from simulating zero pumpage, stream stage at either October 1986, Q_{90}, or Q_{50}, levels, and dry conditions of boundary and semiconfining-unit head, indicate that aquifer discharge to streams and in-channel springs is the largest discharge component, being about 8 times larger than the next largest discharge component (table 10). For simulation of zero pumpage under dry conditions of boundary and semiconfining-unit head and stream stage at October 1986 levels, about 88 percent of the total discharge rate from the Upper Floridan aquifer is attributed to discharge to streams and springs (both in-channel and off-channel), or about 3,004 Mgal/d. The discharge rate to streams and in-channel springs, and the corresponding percentage of total discharge, decreased slightly for the simulation with Q_{50} stream stages, probably because increases in stream stage from October 1986 to Q_{50} levels reduced the hydraulic gradient from the aquifer to streams and in-channel springs from values that were simulated for the October 1986, zero-pumpage conditions. However, off-channel springs, which were simulated as point-discharge functions, were assumed to be unaffected by changes in stream stage. This water-budget component was constant for all simulations because measurements at off-channel springs were not available to support changes to springflow for the various hydrologic conditions represented by simulations. Differences in water-budget components computed for simulations with October 1986 and Q_{90} stream-stage conditions were negligible, as differences in stream stage, aquifer head, and hydraulic gradient between these low-flow conditions were small.

Total daily discharge from the Upper Floridan aquifer under zero pumpage, dry conditions of boundary and semiconfining-unit head, and Q_{50} stream stage is about 92 Mgal less, or about 2.7 percent lower, than the total aquifer discharge under zero pumpage, October 1986 conditions (table 10). However, in comparing results of these simulations, aquifer discharge to streams decreased by about 144 Mgal/d from October 1986 to Q_{50} conditions; the 52 Mgal/d difference (144 Mgal/d minus 92 Mgal/d) is compensated by increases in discharge rates to regional flow (about 35 Mgal/d) and to the undifferentiated overburden (about 17 Mgal/d) from the simulated October 1986 rates. Conversely, the increase in the rate of aquifer recharge from streams computed for the Q_{50} levels was only slightly larger than 1 Mgal/d from that which was simulated for October 1986 conditions. Thus, increases in stream stage that reduce aquifer discharge to streams do not induce an equivalent increase in aquifer recharge from streams.

Table 10. Computed water-budget components for simulations of zero pumpage in Upper Floridan model for dry conditions of boundary and semiconfining unit head, and stream stage at October 1986, Q_{90}, and Q_{50} levels

[Q_{nn} is streamflow that is exceeded *nn* percent of the time; Mgal/d, million gallons per day]

Budget components	Volumetric-flow rates (Mgal/d) by stream-stage condition		
	October 1986	Q_{90}	Q_{50}
Discharge to streams and in-channel springs[1]	2,671	2,636	2,527
Discharge to off-channel springs[2]	332.6	332.6	332.6
Discharge to regional flow	336.1	343.8	370.8
Discharge to undifferentiated overburden	66	69.1	83.6
Total discharge	**3,405.7**	**3,381.5**	**3,314**
Recharge from undifferentiated overburden	2,362	2,349	2,309
Recharge from regional flow	900.8	891.2	866.3
Recharge to Upper Floridan aquifer	119.9	117.8	114.4
Recharge to streams	22.8	23	24
Total recharge	**3,405.5**	**3,381**	**3,313.7**

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

The largest recharge component to the Upper Floridan aquifer for simulations of zero pumpage and stream-stage and boundary conditions just described was vertical leakage through the overlying semiconfining unit consisting of the undifferentiated overburden (table 10). Recharge rates to the Upper Floridan aquifer by vertical leakage through the overlying semiconfining unit composed about 70 percent of the total recharge rate for all zero-pumpage simulations, and were about 2.7 times larger than the next largest recharge component, which was regional flow (excluding flow from outcrop areas). Differences in recharge rates among the zero-pumpage simulations were insignificant, decreasing by about 53 Mgal/d, or about 2 percent, from October 1986 to Q_{50} conditions; thus, it seems that recharge to the Upper Floridan aquifer by vertical leakage is relatively unaffected by changes in stream stage alone.

Regional inflow from the north, west, and east, excluding the outcrop area, was the second largest recharge component to the Upper Floridan aquifer, and provided more than 25 percent of the water supplied to the aquifer. Recharge from the outcrop area of the Upper Floridan aquifer provided about 3.5 percent of the total aquifer recharge. Recharge by streams totalled about 0.7 percent of total recharge to the Upper Floridan aquifer, or, about 1 percent of the recharge from undifferentiated overburden. These budget components varied only slightly among simulations of zero pumpage; thus, indicating that changes in stream stage has a negligible effect on recharge mechanisms to the Upper Floridan aquifer.

Similar relations as those just described for dry conditions of boundary and semiconfining-unit head in the Upper Floridan model were obtained by simulating normal conditions (table 11), although some slight differences are worth mentioning. Ground-water discharge to streams varied by about 2 percent among the zero-pumpage simulations, as in dry conditions; however, discharge rates for normal conditions were about 24 percent larger for each water-budget component than for the same components in dry conditions. This is an important change in ground-water discharge because it reflects an increase in the water resources present in the system under normal conditions, in comparison with dry conditions. The next largest discharge component is springflow, rather than regional flow, as in simulations of dry conditions. Therefore, in the absence of pumpage, springs play an important part in the discharge mechanisms for the Upper Floridan aquifer. Dis-

Table 11. Computed water-budget components for simulations of zero pumpage in Upper Floridan model for normal conditions of boundary and semiconfining unit head, and stream stage at October 1986, Q_{90}, and Q_{50} levels

[Q_{nn} is streamflow that is exceeded *nn* percent of the time; Mgal/d, million gallons per day]

Budget components	Volumetric-flow rates (Mgal/d) by stream-stage condition		
	October 1986	Q_{90}	Q_{50}
Discharge to streams and in-channel springs[1]	3,295	3,295	3,146
Discharge to off-channel springs[2]	332.6	332.6	332.6
Discharge to regional flow	270.9	276.1	294.7
Discharge to undifferentiated overburden	40.7	43.3	55.9
Total discharge	**3,939.2**	**3,911**	**3,829.2**
Recharge from undifferentiated overburden	2,677	2,662	2,618
Recharge from regional flow	1,152	1,140	1,106
Recharge to Upper Floridan aquifer	89.3	87.2	83.7
Recharge to streams	21.3	21.4	21.9
Total recharge	**3,939.6**	**3,910.6**	**3,829.6**

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

charge by regional flow occurs at a fairly constant rate of about 7 percent of total discharge for the 3 simulations of normal conditions. Discharge to the overlying semiconfining unit of the undifferentiated overburden exhibited the most change in proportion to its magnitude; however, the small percentage of the total discharge (about 1 to 1.5 percent) contributed by vertical leakage from the Upper Floridan aquifer is negligible for conditions of zero pumpage.

Recharge to the Upper Floridan aquifer from the undifferentiated overburden for normal conditions and zero pumpage (table 11) occurs at approximately the same percentage of total recharge (about 68 percent) as for dry conditions. A similar relation is indicated for recharge from regional flow, although rates for normal conditions are higher than for dry conditions. Recharge rates from outcrop areas of the Upper Floridan aquifer decrease as simulated stream stage increases from October 1986 conditions to Q_{90} and Q_{50} levels. This trend is consistent for dry conditions (table 10) and normal conditions, except that the rates for normal conditions are about 30-percent lower than for dry conditions. Although recharge rates from outcrop areas constitute less than 4 percent of total recharge to the Upper Floridan aquifer, the reduction in recharge rates that occurs for simulation of normal conditions, compared with dry conditions, reflects higher aquifer-water levels with distance from outcrops for normal conditions than for dry conditions. Although higher ground-water levels under normal conditions cause increased ground-water discharge to streams, increased stream stage for Q_{50} conditions, compared with Q_{90} or October 1986 conditions, helps maintain constant rates of recharge from streams, regardless of dry or normal boundary conditions.

Hydrologic features associated with the largest water-budget components in the Upper Floridan model have the most influence on ground-water resources in the aquifer-stream reservoir system. Aquifer discharge to streams and recharge by vertical leakage from the overlying semiconfining unit of the undifferentiated overburden were the largest water-budget components, hence they have the largest affect on flow and water-resources in the aquifer-stream-reservoir system. Regional inflows and outflows to the Upper Floridan model, including flow from outcrop (recharge) areas, are second in magnitude to stream discharge and recharge by leakage from the overburden. Recharge from streams and discharge to the overburden are of minor impor-

tance to the ground-water resources of the flow system, as they contribute the least amount to the water budget of the Upper Floridan aquifer under zero-pumpage conditions.

Intermediate Model

Computed volumetric-flow rates for water-budget components of the Intermediate model vary in the identical manner for dry and normal conditions, depending only on changes in stream stage (tables 12, 13). The two largest means of ground-water discharge from the Intermediate system are discharge to streams and downward vertical leakage to the Upper Floridan aquifer. Discharge to streams accounts for about 44 percent of total discharge from the Intermediate system for stream-stage conditions of October 1986 and Q_{90}, and about 25 percent of total discharge for Q_{50} conditions. The decrease in discharge to streams is the due to increased stream stage for Q_{50} conditions, compared with Q_{50} and Q_{90} conditions. The increased stream stage causes decreases in hydraulic gradients through, and reduced aquifer discharge across, streambeds and into streams. Vertical downward leakage to the Upper Floridan aquifer occurs at a fairly constant rate for the simulated stream-stage conditions; however, a slight increase in the leakage rate coupled with nearly a 20-percent decrease in total discharge for Q_{50} conditions resulted in discharge to the Upper Floridan aquifer comprising more than 50 percent of the total discharge rate. Conversely, aquifer discharge to regional flow and vertical leakage to the overlying semiconfining unit of terrace and undifferentiated (surficial) deposits (listed in the tables as “undifferentiated overburden”) virtually are unaffected by changes in stream stage.

Recharge to the Intermediate system occurs at nearly the same rates for vertical leakage from the overlying semiconfining unit as for regional flow. These water-budget components each comprise about 25 percent of the total-recharge rate for October 1986 and Q_{90} conditions, and about 30 percent each of the total discharge rate for Q_{50} conditions. The relative increase in recharge rates for these components is attributed to a decrease in the total recharge rate of about 20 percent from the total-recharge rate that was obtained by simulating October 1986 and Q_{90} stream-stage conditions. Decreased upward vertical leakage from the Upper Floridan aquifer for Q_{50} conditions, compared with October 1986 and Q_{90} conditions, is responsible for most of the decreased recharge rate for Q_{50} conditions. Although recharge from streams for Q_{50} conditions exhibited about a 5-fold increase from that obtained for October 1986 and Q_{90} conditions, this water-budget component constitutes only about 3 percent of the total recharge rate to the Intermediate system for Q_{50} conditions, and about 0.5 percent for the other stream-stage conditions.

Changes to recharge and discharge components of the water budget for the Intermediate system indicate that in the vicinity of streams a strong hydraulic connection exists among streams, surficial deposits, the Intermediate system, and underlying Upper Floridan aquifer. Reduced rates of discharge to streams coupled with similar reductions in recharge by vertical leakage from the underlying Upper Floridan aquifer for Q_{50} stream-stage conditions, when compared with October 1986 or Q_{90} conditions, lend support to the concept of a strong hydraulic connection. Previous comparisons of vertical-leakage patterns into and out of the Intermediate system from the overlying semiconfining unit (fig. 22) and the underlying Upper Floridan aquifer (fig. 23) indicate that most of the recharge to the Intermediate system from the underlying Upper Floridan aquifer coincides with areas of discharge to the overlying semiconfining unit. Thus, most of the discharge to the overlying semiconfining unit and to streams is the result of flow-through leakage derived from the underlying Upper Floridan aquifer.

Effects of Pumpage and Boundary Conditions on Flow System

Individual and combined effects of ground-water pumpage and aquifer-boundary conditions of lateral flow, vertical leakage, and stream stage, on flow in the aquifer-stream-reservoir system were evaluated through simulation by using the Upper Floridan model. Because there is no appreciable pumpage in the southern part of the basin, the Intermediate model was used to evaluate flow-system response only to boundary conditions, and was described in the previous section. Simulations of pumpage in 5 multiples of October 1986 rates, combined with changes to boundary conditions, are listed in matrix form (table 1) for ease of reference in this analysis. Each row of this “simulation matrix” corresponds to simulations involving iden-

Table 12. Computed water-budget components for simulations of zero pumpage in Intermediate model for dry conditions of boundary and semiconfining unit head, and stream stage at October 1986, Q_{90}, and Q_{50} levels

[Q_{nn} is streamflow that is exceeded *nn* percent of the time; Mgal/d, million gallons per day]

Budget components	Volumetric-flow rates (Mgal/d) by stream-stage condition		
	October 1986	Q_{90}	Q_{50}
Discharge to streams	43.8	39.8	22.3
Discharge to regional flow	3	3	3
Discharge to undifferentiated overburden	9.8	9.8	10.1
Discharge to Upper Floridan aquifer	43.6	43.7	47
Total discharge	**100.2**	**96.3**	**82.4**
Recharge from undifferentiated overburden	25.6	25.6	25.4
Recharge from regional flow	26.1	25.9	25.7
Recharge to Upper Floridan aquifer	48.1	44.3	28.4
Recharge to streams	0.5	0.5	2.8
Total recharge	**100.3**	**96.3**	**82.3**

Table 13. Computed water-budget components for simulations of zero pumpage in Intermediate model for normal conditions of boundary and semiconfining unit head, and stream stage at October 1986, Q_{90}, and Q_{50} levels

[Q_{nn} is streamflow that is exceeded *nn* percent of the time; Mgal/d, million gallons per day]

Budget components	Volumetric-flow rates (Mgal/d) by stream-stage condition		
	October 1986	Q_{90}	Q_{50}
Discharge to streams	44.2	40.2	22.5
Discharge to regional flow	3	3	3
Discharge to undifferentiated overburden	8.7	8.8	9
Discharge to Upper Floridan aquifer	43.8	43.9	47.4
Total discharge	**99.7**	**95.9**	**81.9**
Recharge from undifferentiated overburden	26.4	26.4	26.2
Recharge from regional flow	26	25.9	25.7
Recharge to Upper Floridan aquifer	46.8	43.1	27.3
Recharge to streams	0.5	0.5	2.7
Total recharge	**99.7**	**95.9**	**81.9**

tical boundary conditions, with only pumpage changed by the multiples of October 1986 rates listed. Each column corresponds to simulations involving 6 different combinations of boundary conditions for the same value of pumpage.

Flow-system response to changes in hydrologic conditions was measured by changes in stream-aquifer flow, boundary flow, and ground-water levels for each simulation of nonzero pumpage defined in the simula-

tion matrix. Changes in these quantitative measures of flow-system response were analyzed by comparing simulation results from pumpage scenarios that use identical boundary conditions, such as along rows of the simulation matrix, and by referencing simulation results to zero-pumpage conditions. The analyses yielded values for stream-aquifer-flow decline, and changes in boundary flow and ground-water level in the Upper Floridan aquifer.

Changes in volumetric-flow rates and in relative percentages that each water-budget component contributed to ground-water pumpage were determined by comparing water budget components derived from simulations of 5 scenarios of pumpage with similar components derived from simulations of zero pumpage. Comparison of water-budget components was made systematically along rows of the simulation matrix for the Upper Floridan model (table 1) to evaluate the effects of pumpage only on the flow system. Effects of pumpage and boundary conditions on water resources in the Upper Floridan aquifer were analyzed in terms of changes to water-budget components and to the percentages that each component contributed to the total-pumping rate. This evaluation is critical in determining probable effects on downstream baseflow caused by rates of ground-water withdrawal from the Upper Floridan aquifer that are possible for given sets of boundary conditions.

Comparison of water budget components derived from simulations of increased pumpage identifies which flow-system components contributed water to the pumped wells (tables 14–19, at the end of this report, p. 100–105). The water-budget component that exhibited the most change in response to increased well discharge was reduced discharge to streams, which is water that would have discharged from the Upper Floridan aquifer to streams under conditions of zero pumpage. Volumetric flow rates and percentages that well discharge contributed to this component indicate a linear relation between pumpage increase and reduced aquifer discharge to streams; that is, doubling the pumpage (from $n=0.5$ to $n=1 \times$ October 1986 rates) causes the reduction in discharge to streams and in-channel springs to double also. About 60 to 62 percent of the pumped water was derived from reduced discharge to streams and in-channel springs for all simulations of pumpage except the 5-fold increase in October 1986 rates ($n=5$; tables 1, 14–19). The slight increase in reduced discharge to streams for multiples of October 1986 pumpage of $n=0.5$, 1, and 2, followed by a consistent decrease for simulations in which $n=5$, reflects increased capture by pumped wells of regional ground-water flow and diversion from its natural drainage to surface-water features (streams). This continues until the pumpage-induced, ground-water-level decline, or drawdown, causes some streams to go dry; thus, the flow system exhibits a nonlinear relation between additional pumpage change and reduced aquifer discharge to streams. Streams that do not go dry with increased pumpage probably have the capacity to convey water from upstream reaches that are minimally affected by pumpage, thus providing means of aquifer recharge to the pumped wells by induced leakage across streambeds into the aquifer. This is indicated in the tables by a consistent increase in the rate of induced recharge from streams for pumpage scenarios defined by $n=0.5$, 1, and 2, followed by a sharp decrease for scenarios where $n=5$, as some streams either recharge the aquifer (by becoming losing streams) or go dry.

Although some induced recharge to the aquifer across streambeds is possible for all scenarios of increased pumpage, actual recharge for conditions of the larger pumping rates likely could be less than simulated. Increased pumpage causes reduced regional ground-water discharge to streams for parts of the stream, or reaches, that might receive ground water for all but extreme increases in pumpage. Reduced streamflow corresponds to a decrease in stream stage for the increased-pumpage scenarios and a reduction to vertical hydraulic gradients in those parts of the streambed where induced recharge to the aquifer occurs. These reaches might or might not differ from reaches that receive regional ground-water flow, or aquifer discharge, during conditions of less pumpage. The ultimate reduction in stream stage would cause the stream to go dry, and, for a dry stream, no induced recharge is possible. The model allowed for drying conditions of certain streams that were located in upland areas of the basin for cases where aquifer head dropped below the bottom of the streambed. However, for other streams, the model simulated a virtually unlimited source of water available in the stream channel for pumpage-induced recharge to the aquifer even though the aquifer head dropped below the streambed bottom; the model did not simulate decreases in stream stage corresponding to pumpage-induced streamflow reductions. Because increases in pumping rates cause reduced streamflow and

lower stream stage, which was not simulated in the Upper Floridan model, values of induced recharge to the aquifer from streams, listed in tables 14–19, probably are larger than actually would occur for pumpage multiples larger than twice the October 1986 rates.

A detailed analysis of stream-aquifer-flow decline due to ground-water pumpage can be used to identify specific reaches that might go dry under increased-pumpage conditions, provided that streamflow for the reach is known. This was performed in the following section, where pumpage-induced reductions in the ground-water component of streamflow are determined for 37 reaches for which upstream and downstream flow rates in the stream channel were known.

Commensurate with a pumpage-induced decrease in ground-water discharge to streams were increases in rates of induced recharge from regional flow and the overlying semiconfining unit of the undifferentiated overburden. Changes to these water budget components represent, respectively, increases in lateral and vertical movement of ground water into the Upper Floridan aquifer in response to increased pumpage demand.

Areas of induced recharge probably coincide with that indicated on plate 11. Recharge through sinkholes, swallowholes, and shallow depressions might occur in areas where discharge is indicated on plate 11. However, as explained previously, these features affect a small area on a local scale, which cannot be depicted at the regional scale of the illustration.

Like induced recharge from streams, the ability of the flow system to supply water to the aquifer by vertical leakage and regional flow for the long term is problematic because of the relation between flow rates and the head differences that govern flow rates. It is unrealistic to assume that hydraulic head in the overburden or in the aquifer region external to the model area would be unaffected by increased pumpage or prolonged drought. Head in aquifer material adjacent to the model area and in the overburden likely would be lower than October 1986 levels if pumpage increases occur during more severe or prolonged drought conditions than experienced in 1986. Therefore, corresponding flow rates across lateral and vertical boundaries most likely would be less than simulated. However, smaller flow (recharge) rates from lateral-boundary flow and vertical leakage to the Upper Floridan aquifer than simulated each affect the water budget of the stream-aquifer system to different degrees. Because the percentage that regional flow contributes to pumpage-induced aquifer recharge is small for all pumpage scenarios—a maximum of about 6 percent for the largest increase to pumping rates (tables 14–19)—it seems unlikely that changes in head outside the study area would have a large affect on water-budget components and water levels in the study area. Conversely, induced recharge from the undifferentiated overburden ranges from about 21 to 26 percent of the volumetric flow rate from pumpage increases (tables 14–19). Therefore, it is likely that clayey sediment in the overburden eventually would dewater under conditions of increased pumpage or prolonged drought; this would cause a reduction in vertical-leakage rates from those listed in the tables. If normal seasonal precipitation does not occur following drought conditions, then recharge by infiltration of precipitation through the overburden might be eliminated completely as a source of water to the Upper Floridan aquifer.

In the same manner as with induced recharge by streams, linear flow-system response to pumpage is indicated by the constant percentage of well discharge that these water-budget components supply for all multiples of October 1986 pumpage except $n=5$. Between one-fifth and one-quarter of the ground water pumped from the Upper Floridan aquifer in all scenarios was derived from induced recharge by vertical leakage from the undifferentiated overburden; the smaller percentage corresponds to dry conditions of boundary and semiconfining-unit head and pumpage at a multiple of 5 times the October 1986 rate (tables 14, 16, 18). The largest percentage of induced recharge from the undifferentiated overburden was achieved under normal conditions with stream stage and pumpage at October 1986 levels (table 15). However, differences in volumetric rates and percentages of well discharge that are supplied by induced recharge from the undifferentiated overburden are not large enough to draw attention to changes in boundary conditions and stream stage as a major influence on this water-budget component.

One apparent result of the simulations is that the percentage of well discharge supplied by induced recharge by vertical leakage from the undifferentiated overburden is nearly constant for all pumpage scenari-

os (about 25 percent, tables 14–19). This indicates a linear response of the Upper Floridan aquifer to changes in pumpage, that is, as the pumping rate doubles, the rate of induced recharge by vertical leakage also doubles. The importance of this result is that vertical leakage was represented in the Upper Floridan model as a nonlinear hydrologic process, where the nonlinearity in leakage occurs in areas where the aquifer converts from confined to unconfined (water-table) conditions. The nearly constant percentages that are listed for this water-budget component in tables 14–19, and the apparent linearity of the vertical-leakage rates, indicate that pumpage in the Upper Floridan aquifer at the simulated rates has only a minor effect on the relative size and distribution of aquifer areas that are either confined or unconfined. A further interpretation of the water-budget rates and percentages is that the area over which the aquifer exhibits water-table conditions is small, if not, then extensive areas of water-table conditions would create nonlinear-leakage rates which would be manifested in smaller recharge rates (and percentages) than simulated. A slight decrease in the percentages corresponding to induced recharge by vertical leakage does occur for pumpage at 5 times the October 1986 rates ($n = 5$ pumpage scenarios, tables 14–19), indicating that increased pumpaged causes some aquifer dewatering and conversion from confined to water-table conditions locally.

The linear response of the aquifer to pumpage does not seem to be affected by changes in head from dry to normal conditions along lateral or vertical boundaries. Therefore, relations that are established between increased pumpage and stream-aquifer-flow decline for one set of hydrologic-boundary conditions can be used to explain similar relations corresponding to another set of conditions, provided both sets of conditions allow the flow system to behave in a linear manner.

Values of hydraulic head in the undifferentiated overburden or in the aquifer external to the modeled area may decline in response to increased discharge to wells, a condition not simulated in the Upper Floridan model. Pumpage-induced reductions in lateral-boundary head and head in the overburden would cause smaller rates of induced recharge from these sources than was simulated, because flow rates depend on head differences either between the aquifer and the overlying semiconfining unit (for vertical leakage from the undifferentiated overburden) or across an external-model boundary (for regional flow). Because the percentage that regional flow contributes to increased discharge to wells is small for all pumpage scenarios (less than 6 percent for the largest increase to pumping rates), it is unlikely that induced recharge from regional flow would change appreciably from the values listed in tables 14–19. In comparison, the larger amount of induced recharge from the undifferentiated overburden, about 25 percent of the pumping rates, makes it likely that hydraulic head in and induced aquifer recharge from the overlying semiconfining unit eventually would decrease for sustained periods of increased pumpage. The temporal lag for head changes in the aquifer to reach the distal side of the overlying semiconfining unit and effect head declines there is dependent on hydraulic characteristics of the semiconfining unit, such as thickness, vertical hydraulic conductivity, and specific storage, in addition to the duration of sustained pumpage increases. Analysis of these transient responses of the overburden to pumpage is beyond the scope of the present study.

Other water-budget components collectively, and thus individually, had only a minor influence on meeting the demand for water imposed by pumped wells. Reduced discharge to regional flow exiting the study area across model boundaries to the east and south and induced recharge from regional flow, not including the outcrop area, constituted between 6 and 4 percent, respectively, of the pumping rates. Between 1 and 4 percent of the pumping rate was derived from reduced discharge to the overlying semiconfining unit, that is, the capture by wells of water that would have discharged upward by vertical leakage to the overburden. Only about 2 percent of the pumped water was derived from the outcrop (recharge) areas, and this did not change appreciably with changes in pumping rates or boundary conditions.

Stream Aquifer Flow Decline

Response of the aquifer-stream-reservoir system to simulated pumpage in the Upper Floridan aquifer is measured by changes in flow rates, or stream-aquifer flow, across streambeds. As the dominant direction of this flow is from the aquifer to streams, response of the system to pumpage is measured in terms of pumpage-induced, stream-aquifer flow decline. Because some streams or reaches also provide recharge to the

Upper Floridan aquifer, net stream-aquifer flow was determined, where net flow is aquifer discharge to the stream minus stream recharge to the aquifer. Net stream-aquifer flow was computed for 37 reaches in the Upper Floridan model (pl. 9), which is the number of reaches that contained enough streamflow data for October 1986 to permit this analysis. Net stream-aquifer flow generated by the calibrated Upper Floridan model and values derived from streamflow measurements have been compared in Torak and others (1996), and is not repeated here. Instead, comparisons were made using computed values of net stream-aquifer flow corresponding to simulation of 4, nonzero multiples of October 1986 pumpage in the Upper Floridan aquifer and various combinations of boundary conditions listed in the simulation matrix (table 1) to determine effects of pumpage and boundary conditions on the aquifer-stream-reservoir system.

Changes in net stream aquifer flow resulting from simulated pumpage indicated that nearly all of the 37 reaches evaluated received less water from the Upper Floridan aquifer as pumpage was increased (tables 20–25, at the end of this report, p. 106–111). (Positive values of stream-aquifer flow listed in these tables represent aquifer discharge to the stream or reach.) This trend does not seem to be affected by changes in boundary and semiconfining-unit head from dry to normal conditions, or by increases in stream stage from October 1986 to Q_{90} to Q_{50} levels; stream reaches consistently lose water as pumpage increases, either by reduced aquifer discharge to the reach or by induced recharge from the reach to the aquifer. A few exceptions are worth noting, namely, reach 25, Kinchafoonee Creek, which is a losing-stream reach and seems to be unaffected by changes in pumpage or boundary conditions, and reach 37, Apalachicola River, which is at least 30 mi from pumped wells in the Upper Floridan model (pl. 11). However, this is not to say that streamflow in the Apalachicola River is unaffected by pumpage in the Upper Floridan aquifer; quite to the contrary. Declines in stream-aquifer flow induced by any hydrologic stress, not only pumpage, cause reductions in the baseflow of streams, which, in turn, reduce stream stage and streamflow in downstream reaches from where the stream-aquifer-flow decline has occurred. Thus, stream-aquifer-flow declines upstream of the Apalachicola River will reduce flows entering Lake Seminole and, subsequently, cause reductions in flow of the Apalachicola River. Alternately, negative stream-aquifer flow indicates a losing stream, such as reach 34, Flint River. As described previously, the losing-stream reach might or might not actually provide water to the aquifer; this depends on whether there is sufficient streamflow entering the losing reach from upstream to provide aquifer recharge at the rate indicated in the tables.

In addition to pumpage-induced, baseflow reduction of streams, some streams experienced the ultimate baseflow reduction for larger multiples of October 1986 pumpage (n=2 and 5, tables 20–25) by either transforming from gaining to losing streams or by going dry. Losing streams are indicated in the tables by negative values of stream-aquifer flow and a dry reach is indicated by a zero value of flow.

By computing flow for specific stream reaches, rather than for entire streams, parts of the river basin that are affected most by pumpage, or pumpage change, were identified. Because small streams in upland areas were simulated as "discharge-only streams," it was assumed that the stream would cease to flow in these areas if aquifer head dropped below the bottom of the streambed. Hence, these streams would not have the streamflow to recharge the Upper Floridan aquifer and would go dry under the larger multiples of October 1986 pumpage. Streams such as Gum Creek (reach 1), Jones Creek (reach 4), Cooleewahee Creek (reach 7), and Spring Creek (reaches 14 and 18) had net stream-aquifer flows of zero, indicating that they had gone dry during simulation of pumpage increases (tables 20–25; pl. 11). Dry-stream conditions for these reaches were less numerous for normal levels of boundary and semiconfining-unit head (tables 21, 23, 25) than for dry conditions (tables 20, 22, 24). Other streams or stream reaches were nearly dry for simulation of various boundary conditions and stream stage and October pumpage in multiples of 2 and 5, as net stream-aquifer flow was reduced to less than 0.3 cubic feet per second (ft^3/s) (see tables 20–25 and plate 11 for identification of these reaches and their location in the study area). Thus, it can be assumed that these areas of the river basin would experience diminished flow exchange between ground- and surface water caused by increased pumpage from the October 1986 rates.

Four reaches of streams larger than those that were simulated as dry contained negative stream-aquifer flows, indicating losing streams that recharge the aquifer: Muckalee Creek (reaches 22 and 23), Kinchafoo-

nee Creek (reach 25), and one reach of the Flint River (reach 43). As described above, whether these reaches actually provide recharge to the Upper Floridan aquifer depends on whether flow entering the reach from upstream is sufficient to meet the demand, as indicated by a negative stream-aquifer flow. Muckalee and Kinchafoonee Creeks rise outside of the study area in Coastal Plain sediments located northwest of the outcrop of the Upper Floridan aquifer (pl. 11). Thus, it is likely that sufficient flow enters the study area to meet the recharge demand imposed on these streams by simulated pumpage in the Upper Floridan aquifer. The losing reach of the Flint River is located between its confluence with Ichawaynochaway Creek and Bainbridge. Because this is the last reach of the Flint River before it empties into Lake Seminole, it also is likely to contain sufficient flow from upstream reaches to meet the aquifer-recharge demand placed on it by simulated pumpage; notwithstanding that the largest decreases in pumpage-induced, stream-aquifer-flow declines, hence baseflow reductions, occur upstream of this losing reach of the Flint River.

Stream-aquifer flows that correspond to streams located on the western side of the Chattahoochee and Apalachicola Rivers in Alabama, and on the Chipola and Apalachicola Rivers in Florida, seemed to be least affected by pumpage in the Upper Floridan aquifer. In the case of the Chipola River, small streams such as Cowarts Creek, Marshall Creek, and Dry Creek (Fla.) virtually were unaffected by pumpage, a result more of the sparse availability of irrigation-pumpage data in northwestern Florida and southeastern Alabama than the reality of only a few wells placed there. Decreases to base flow in the Apalachicola and Chipola Rivers seem to be minimal, although streamflow in the Apalachicola River throughout its course in Florida can be reduced by decreased baseflow of the Flint and Chattahoochee Rivers and of Spring Creek. Flow in the Apalachicola River and to Apalachicola Bay depend primarily on streamflow in the Chattahoochee and Flint Rivers, Spring Creek, and their tributaries, which incur pumpage-induced, stream-aquifer-flow declines. In addition, the ability to maintain the level of Lake Seminole also can be affected by decreased base flow of these surface water features and by ground-water-level declines in areas adjacent to the Lake.

Changes in Boundary Flow

The combined effects of pumpage and boundary conditions on ground-water flow across hydrologic and political boundaries of the study area were analyzed by using water-budget components derived from the Upper Floridan and Intermediate models. Volumetric rates of water entering and exiting the study area from outcrop areas, across basin divides, and across state lines (fig. 24) were obtained from simulation of hydrologic conditions listed in tables 1 and 2. These rates represent regional-flow components to the Upper Floridan aquifer and to water-bearing units of the Intermediate system. Simulation was used to identify possible causes for changes in magnitude and direction of regional-flow components and to quantify the effects of such changes on the flow system. Changes to regional-flow components across any model boundary indicate changes in the availability of ground- and surface-water resources in specific areas of the basin and can adversely affect development potential of the resource.

Volumetric rates of lateral-boundary flow by State were computed from simulations with the Upper Floridan model for various pumpage scenarios, dry and normal conditions of boundary and semiconfining-unit head, and stream stage at October 1986, Q_{90}, and Q_{50} levels (tables 26–31, at the end of this report, pages 112–117); positive values indicate recharge across the boundary. Simulation results indicated that pumpage either induces more water to flow across lateral boundaries into the Upper Floridan aquifer or reduces the amount of water flowing out, compared with rates that would exist under no pumpage. An exception to this occurs along the southern part of the Solution Escarpment in Georgia (boundary-segment 7, fig. 24; tables 26, 28, 30), where, for all levels of stream stage and dry conditions of boundary and semiconfining-unit head, boundary flow is reversed from discharge to recharge for simulated pumpage in multiples of 2 and 5 times the October 1986 rates. However, for normal conditions of boundary and semiconfining-unit head and for all levels of stream stage and pumpage, flow across this boundary recharges the Upper Floridan aquifer; no reversals of ground-water flow were simulated (tables 27, 29, 31).

Changes in boundary and semiconfining-unit head from dry to normal conditions, in the absence of changes in pumpage and stream stage, have a pronounced effect on several lateral-flow boundaries to the

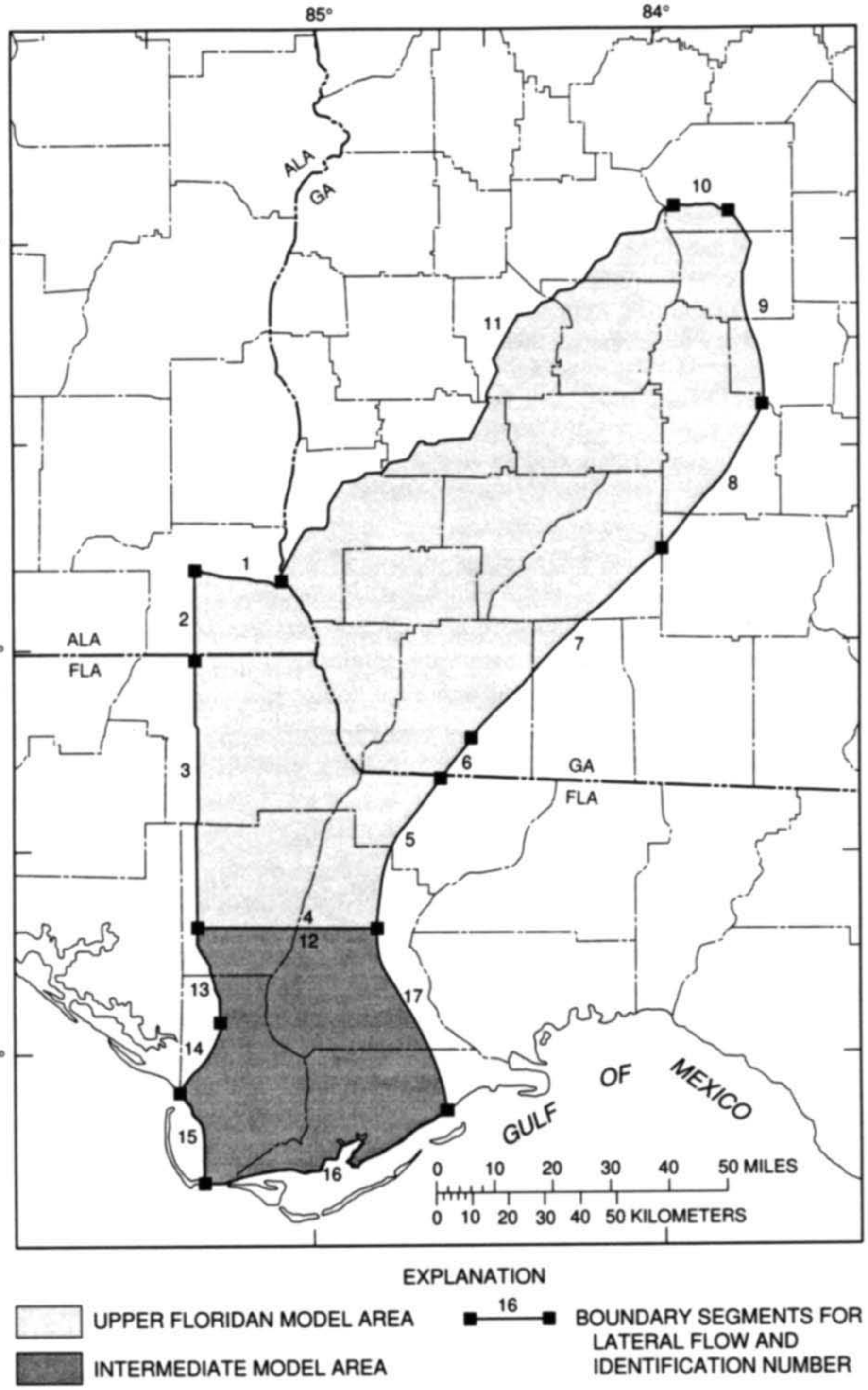

Figure 24. Boundary segments for lateral flow to the Upper Floridan and Intermediate models.

Upper Floridan model. In the absence of pumpage, these changes increase the amount of ground water in the study area by increasing inflow across some lateral boundaries. Although pumpage also increased inflow across lateral boundaries, inflows caused by changes in boundary conditions from dry to normal conditions, in the absence of pumpage, increases the amount of water available for development by pumpage. Regional outflow is reversed to inflow across the southern boundary in Florida, and across the southeastern boundary and southern part of the Solution Escarpment in Georgia (boundary-segments 4, 6, and 7, respectively,

in tables 26–31; fig. 24). In Alabama, inflow to the Upper Floridan aquifer from outcrop areas (boundary-segment 1, fig. 24; tables 26–31) is larger for normal conditions than for dry conditions by factors that range from about 3 to 4.6 times the dry rates; the smallest increases were caused by the largest simulated pumping rate. In Georgia, however, inflow from outcrop areas under the same (normal) conditions occurs at rates that are 40 to 50 percent less than values obtained for corresponding dry conditions, and the largest reduction in recharge is associated with the smallest simulated pumpage (boundary-segment 11, fig. 24; tables 26–31).

Lateral flow across state lines is limited by the hydraulic effect of the Chattahoochee River and Lake Seminole. The hydraulic gradient to the Chattahoochee River from Alabama, Florida, and Georgia (pl. 10) prevents ground water from flowing across parts of state lines that are established along the River; thus, no interstate ground-water flow occurs across the River. Similarly, the broad expanse of Lake Seminole coupled with its distance from upland recharge areas causes the potentiometric surface of the Upper Floridan aquifer to be nearly horizontal, inhibiting flow of ground water between Alabama and Georgia and between Florida and Georgia.

Interstate flow of ground water occurs where the state boundaries do not coincide with surface-water features. Ground water flows from Alabama to Florida and from Georgia to Florida across the straight, east-west trending parts of the state lines shown on figure 24. For October 1986 conditions, about 140 Mgal/d flows from Alabama to Florida across about 20 miles of state line located in extreme northwestern Florida. Similarly, about 20 Mgal/d flows from Georgia to Florida across about 15.5 miles of state line located east of Lake Seminole. These flows were computed using the following estimates of average hydraulic properties for the Upper Floridan aquifer:

Property	Boundary flow: Alabama-to-Florida	Boundary flow: Georgia-to-Florida
Aquifer thickness (ft) (pl. 3)	140	600
Hydraulic conductivity (ft/d) (pl. 6; table 7)	1,600	1,300
Hydraulic gradient (ft/ft) (pl. 10)	0.0008	0.00004

Interstate ground-water flows will be affected by changes in pumpage and boundary conditions because these will change aquifer thickness and lateral hydraulic gradient across state lines from the values that represent October 1986 conditions. Because only the potentiometric surface for October 1986 was prepared in this study, values for hydraulic gradient and thickness that would correspond to pumpage scenarios other than October 1986 are not available. However, inferences about how pumpage might affect interstate ground-water flow can be made by interpreting pumpage-induced, ground-water-level change at state boundaries with regard to changes in aquifer thickness and hydraulic gradient. Water-level-change maps presented in the following section might be useful for drawing such hydrologic inferences about interstate ground-water flow.

Changes in flow rates from outcrop areas in Alabama and Georgia caused by changes in boundary and semiconfining-unit head affect the percentage that each state contributes to total recharge of the Upper Floridan aquifer. Under dry conditions, about 6 to 8 percent of total recharge from outcrop areas was supplied to the Upper Floridan aquifer from Alabama; for normal conditions, this percentage increased to about 30 to 40 percent. The change in boundary and semiconfining-unit head from dry to normal conditions caused decreased recharge from outcrop areas in Georgia and increased recharge from Alabama, resulting in a large relative increase in the Alabama contingent of recharge. However, this apparent shift in recharge emanating from outcrop areas in Alabama as opposed to Georgia is relatively unimportant considering that inflow from outcrop areas is volumetrically small, constituting less than 2 percent of the simulated net inflow to the model area under dry conditions and less than 5 percent under normal conditions. In addition, induced recharge from outcrop areas composed less than 2 percent of the water pumped from the Upper Floridan aquifer under dry or normal conditions (tables 14–19).

Effects on boundary flows of changing stream stage from October 1986 levels to those corresponding to Q_{90} or Q_{50} flows are not consistent at each lateral-flow boundary and are compounded by changes to bound-

ary and semiconfining-unit head and pumpage. For most lateral-flow boundaries, changes to stream stage have minimal effects on boundary flows. However, simulated flows across the southern part of the Solution Escarpment in Georgia and southern boundary in Florida exhibit larger stream-stage effects than other lateral boundaries, and these effects are exacerbated by changes in boundary conditions and pumpage. For dry and normal conditions, increased stream stage from October 1986 to Q_{50} levels caused an increase in boundary flow across the southern part of the Solution Escarpment of about 14.5 Mgal/d, which either increased outflow or decreased inflow in comparison with October 1986 rates (tables 26–31). In addition, the 14.5-Mgal/d increase caused a flow reversal across this boundary for simulation of dry conditions and pumpage at a multiple of twice the October 1986 rate; whereas inflow occurred for simulations with October 1986 and Q_{90} stream stages, outflow occurred with Q_{50} stream stages. For normal conditions of boundary and semiconfining-unit head, boundary inflow is simulated across the southern part of the Solution Escarpment in Georgia for all combinations of stream stage and pumpage.

The effect of simulated increases in stream stage from October 1986 to Q_{50} levels on the southern boundary of the Upper Floridan model in Florida was to approximately double outflow under dry conditions and reduce by half the inflow under normal conditions. The net change in flow across this boundary caused only by changes from dry to normal conditions is about 53 Mgal/d for all levels of simulated pumpage and stream stage. For all pumpage scenarios using the Q_{90} stream stage, inflow and outflow rates are approximately equal, about 26.5 Mgal/d (tables 28 and 29).

The largest components of regional flow entering the Upper Floridan aquifer among the three states are inflows across the southwestern and southeastern model boundaries in Florida (boundary-segments 3 and 5, respectively, fig. 24, tables 26–31). Slightly less than half of the total regional inflow to the Upper Floridan model crosses the southwestern model boundary for dry conditions; slightly more than half enters for normal conditions. Inflow across the southeastern model boundary is about half of the inflow rate across the southwestern boundary.

Regional flow in the Upper Floridan aquifer across lateral-model boundaries in Florida is not affected appreciably by changes to only pumpage. Flow rates across these boundaries vary by less than 10 percent when compared with results of simulations in which only pumpage was changed (tables 26–31). As discussed previously, the apparent insensitivity of the flow system in Florida to pumpage probably is the result, in part, of the lack of available pumpage data in this area for October 1986; hence only a few wells were simulated in Florida. However, corresponding to large regional inflows to the Upper Floridan aquifer in Florida are some of the largest stream-aquifer flows in the study area (tables 20–25), where the aquifer seems to be well drained by the Chipola and Apalachicola Rivers. Therefore, large regional-flow components to the Upper Floridan aquifer in Florida seem to provide the base flow of these streams.

Boundary flows to the Intermediate model are contained entirely in Florida and indicate a relative insensitivity to simulated changes in stream stage and boundary conditions (tables 32, 33). In comparison with boundary flows to the Upper Floridan model, the Intermediate system seems to contain a limited source of ground water, neither conveying large amounts of ground water laterally across boundaries nor supplying large amounts of water to wells. Inflow to the Intermediate model across lateral boundaries totals about 3 Mgal/d for all conditions simulated. This small amount of boundary inflow easily is accounted for by ground-water discharge to streams and vertical leakage to overlying and underlying semiconfining units.

Ground-Water-Level Change

Ground-water-level change in the Upper Floridan aquifer and Intermediate system was computed in response to simulated changes in pumpage and boundary conditions from those that existed in October 1986. Changes in ground-water levels were obtained for each scenario listed in the simulation matrices (tables 1; 2) by subtracting nodal values of simulated water levels from similar values corresponding to October 1986 conditions; hence, ground-water-level change is referenced to water levels computed by the calibrated Upper Floridan and Intermediate models. Nodal values represent simulated ground-water-level change at distinct

Table 32. Computed lateral-boundary (regional) flow in Florida from Intermediate model, simulating stream stage at October 1986, Q_{90}, and Q_{50} levels and dry conditions of boundary and semiconfining-unit head

[Q_{nn} is streamflow that is exceeded *nn* percent of the time; Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Lateral-boundary flow (Mgal/d) by stream-stage condition		
		October 1986	Q_{90}	Q_{50}
12	Northern boundary	1.96	1.95	1.92
13	Northwestern boundary	.67	.67	.67
14	No flow	0	0	0
15	Southwestern boundary	.3	.3	.3
16	Southern boundary	.15	.15	.15
17	Basin divide, no flow	0	0	0

Table 33. Computed lateral-boundary (regional) flow in Florida from Intermediate model, simulating stream stage at October 1986, Q_{90}, and Q_{50} levels and normal conditions of boundary and semiconfining-unit head

[Q_{nn} is streamflow that is exceeded *nn* percent of the time; Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Lateral-boundary flow (Mgal/d) by stream-stage condition		
		October 1986	Q_{90}	Q_{50}
12	Northern boundary	1.96	1.94	1.91
13	Northwestern boundary	67	.67	.67
14	No flow	0	0	0
15	Southwestern boundary	.3	.3	.3
16	Southern boundary	.15	.15	.15
17	Basin divide, no flow	0	0	0

points that can be compared with actual water-level change in wells. Relative ground-water-level change, either higher or lower than October 1986 levels, indicates, respectively, an increase or decrease in available water resources or development potential of the flow system.

Upper Floridan aquifer

Comparisons of water-level-change distributions resulting from dry and normal boundary conditions, stream stage at October 1986, Q_{90}, and Q_{50} levels, and pumpage variations from October 1986 rates (figs. 25–42, at the end of this report, p. 118–135) indicate the relative importance and area-specific influence that these hydrologic features have on the shape of the potentiometric surface and on ground-water resources of the Upper Floridan aquifer. In Georgia, ground-water resources seem to be affected more by pumpage and stream stage than by lateral-flow boundaries because most of the ground-water-level change is centered

around areas of heavy-irrigation pumpage and surface-water features. In Alabama and Florida, boundary conditions and stream stage seem to exert a greater influence on the Upper Floridan aquifer than pumpage, probably the result of either sparsely distributed pumpage in October 1986, poorly defined pumpage data, or both. The influence of stream stage on ground-water levels in Florida is demonstrated more clearly on water-level-change maps associated with dry boundary conditions than normal conditions. In Georgia, the opposite is true, because elongated zones of surface-water induced changes to ground-water levels are recognized more easily on maps corresponding to normal boundary conditions than to dry conditions.

Nearly every distribution of water-level change depicted on the maps (figs. 25–42) shows the influence of surface-water features on ground-water levels in the Upper Floridan aquifer. Surface-water features such as the Chattahoochee and Flint Rivers, Spring Creek, and Lakes Blackshear and Seminole influence ground-water levels by either reducing water-level changes in response to pumpage and boundary-condition variations or by inducing ground-water-level change in the vicinity of changed stream stages. These effects are characterized as elongated patterns of ground-water-level change located adjacent to surface-water features. In some instances, the distribution of ground-water-level change is altered to the extent that apparent circular patterns of contours of ground-water-level change are bounded by surface-water features.

Ground-water levels increased in comparison with October 1986 levels for all simulations using half of the October 1986 pumpage (figs. 25–30). Under dry conditions, a maximum water-level increase of slightly more than 10 ft occurs west of the Flint River in central Lee County, Ga. (figs. 25–27). Increasing stream stage from October 1986 levels to Q_{90} and Q_{50} levels broadens the area enclosed by the 10-ft contour of water-level change in this region. Increases in October 1986 ground-water levels of slightly more than 4 ft occur in west-central Miller County, Ga., and expand to cover over half of the county for increases in stream stage from October 1986 to Q_{50} levels (fig. 27). In the Miller County area, the combination of a dense distribution of well pumpage (pl. 7), relatively small aquifer thickness (pl. 3), and relatively low aquifer hydraulic conductivity (1,300 ft/d in zone 34; table 7; pl. 6) allow pronounced changes in ground-water levels to occur due to changes in pumpage.

Simulation of normal conditions of boundary and semiconfining-unit head, half of the October 1986 pumpage, and stream stage at October 1986, Q_{90}, and Q_{50} levels creates a more wide-spread and diverse distribution of water-level increases than simulated for dry conditions (figs. 28–30). Maximum ground-water level increase is slightly more than 15 ft, located in the same area of Lee County, Ga., as the 10-ft increase under dry conditions. A 10-ft water-level increase is located in Early County, Ga., and 6 to 8 ft increases are centered about the western parts of Crisp, Dougherty, Lee, and Worth Counties, Ga., and in southeastern Calhoun County, Ga. Ground-water levels for about one-half to two-thirds of Baker County, Ga., exhibit increases ranging from about 4 to 6 feet; the larger water-level increases are associated with stream stage at Q_{50} levels. Zones of 10-ft water-level increase develop around the western, southwestern, southern, and southeastern boundaries of the model area in Alabama and Florida, and a 15-ft increase occurs along the northern boundary in Alabama, all of which seem to be a direct result of increases to head controlling lateral-boundary flow rather than decreased pumpage from within the model area.

Water-level change maps based on simulated pumpage at 2 and 5 times the October 1986 rates and dry conditions of boundary and semiconfining-unit head show similar patterns that are similar in size but vary greatly in magnitude of water-level change and in the hydrologic implications represented with each pattern (figs. 31–36). For all scenarios of increased pumpage, water-level decline, or drawdown, is centered around 5 areas, all located in the northern part of the model area. The largest of these areas is in Miller County, Ga.; the next-largest area is located in eastern Lee County, Ga., between Muckalee Creek and the Flint River. For twice the October 1986 pumpage, a minus-10-ft contour of water-level change (or 10 ft of drawdown, as drawdown is always positive) is centered between these surface-water features. For simulated pumpage at 5 times the October 1986 rate, the area in Lee County experienced more than 70 ft of ground-water level decline, which exceeds the estimated-aquifer thickness in this area (figs. 32, 34, 36). Hence, in this area, the aquifer might experience dewatering, or drying, due to pumpage at this rate. Similar aquifer drying is indicat-

ed for parts of Miller County, Ga., in the area enclosed by the minus-60-ft contour of water-level change with respect to October 1986 levels.

A small but distinct drawdown pattern exists in western Mitchell County between the Flint River and the Big Slough under dry conditions (figs. 31–36). Here, increased stream stage from October 1986 to Q_{50} conditions seems to be more effective at reducing ground-water level decline for pumpage at twice the October 1986 rate than for pumpage at 5 times the October rate. For the simulation using Q_{50} stream stage and pumpage at twice the October 1986 rate (fig. 35), ground-water levels in this area exhibited less than 2 ft of decline, whereas about 5 ft of water-level decline was indicated for simulated pumpage at 5 times the October 1986 rate (fig. 36).

Areas of ground-water-level change for scenarios of pumpage and stream stage that use normal conditions of boundary and semiconfining-unit head are smaller than those areas associated with simulations of dry conditions (figs. 37–42). The small drawdown pattern in western Mitchell County that develops at twice the October 1986 pumping rate under dry conditions does not develop under normal conditions. Unlike patterns of water-level change that formed under dry conditions, which create local affects, patterns of water-level change for normal conditions affect a larger areas for pumpage that is 2 to 5 times the October 1986 rate. Maximum drawdown exceeds 60 ft in Lee and Miller Counties, Ga., for simulated pumpage at 5 times the October 1986 rate. As with previous pumpage scenarios, the Upper Floridan aquifer could undergo dewatering in these areas for simulated pumpage at 5 times the October 1986 rate. Water-level decline from pumpage at twice the October 1986 rate did not produce dry conditions in the Upper Floridan aquifer for simulations that varied stream stage.

The susceptibility of parts of the Upper Floridan aquifer to experience dewatering in response to simulated pumpage can be evaluated by comparing aquifer thickness with drawdown distributions from each pumpage scenario (pl. 3; figs. 25– 42). From these comparisons, the Upper Floridan aquifer has the potential to undergo dewatering in the following areas in Georgia for pumpage at 5 times the October 1986 rate:

- Crisp and Dooly Counties, east of Lake Blackshear and northwest of Cordele
- Lee County, between Muckalee Creek and the Flint River
- Miller County, between Dry and Spring Creeks and west of Boykin
- Early and Seminole Counties, north of Donalsonville

Ground-water-level-change maps derived from changes in simulated pumpage in the calibrated Upper Floridan model that were made while maintaining boundary conditions and stream stage at October 1986 levels (row one, or R1P*n* simulations, $n = 0.5$, 1, 2, 5, of simulation matrix, table 1) indicate a linearity in flow-system behavior (figs. 25, 31, 32). Comparison of water-level-change patterns on these maps indicates that changes in pumpage by multiples of the October 1986 rate produces corresponding multiples of water-level change in some areas. For example, water-level changes that were obtained from simulating half of the October 1986 pumpage are about half of that obtained from simulating twice the October 1986 pumpage. The common multiple in this case is 2, as the change in pumpage associated with twice the October 1986 pumpage (475 Mgal/d) is 2 times larger than the pumpage decrease of about 237 Mgal/d associated with the 0.5 multiple of pumpage. Notwithstanding that a pumpage decrease is simulated in one case and an increase in the other, the linear response of the aquifer-stream-reservoir system to pumpage, particularly the Upper Floridan aquifer, indicates that quantifiable changes in pumping rates can produce equally quantifiable changes in ground-water levels. Such relations of pumpage to ground-water levels in the Upper Floridan aquifer are necessary for evaluating resource availability.

Further proof of linear-flow-system response to either positive or negative pumpage change is contained in the comparison of computed drawdown (negative ground-water-level change) (fig. 43), from a previous study of the lower ACF River Basin by Torak and others (1996), with ground-water-level change corresponding to simulated pumpage at half ($n = 0.5$) of the October 1986 rate (fig. 25). The drawdown map depicts ground-water-level change in the Upper Floridan aquifer in response to an increase in simulated pumpage at a multiple of 1.5 times the October 1986 rate; the change in pumpage (237 Mgal/d) is identical to, but oppo-

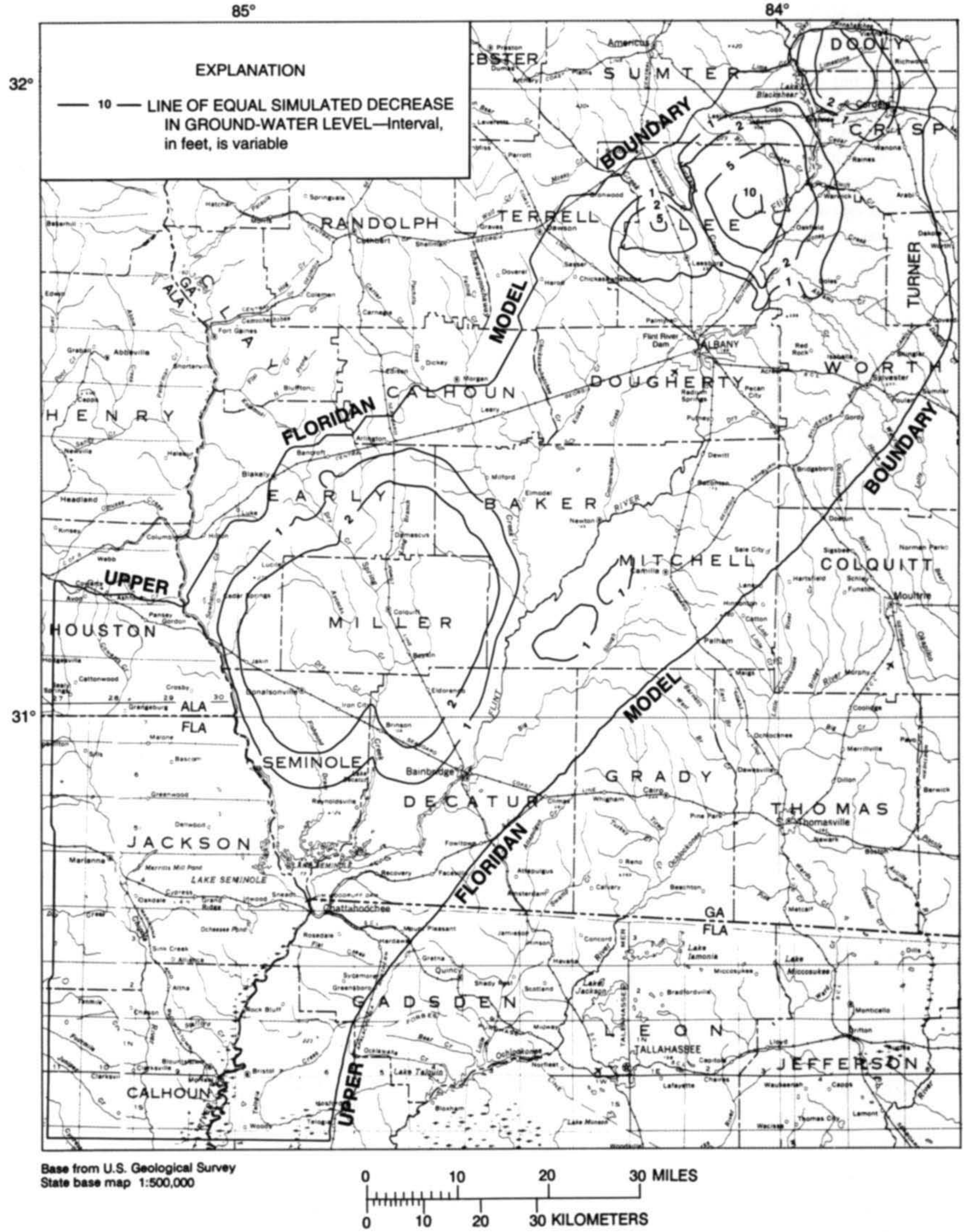

Figure 43. Lines of equal computed drawdown in Upper Floridan aquifer from simulation of increase in October 1986 pumping rates by factor of 1.5, stream stage at October 1986 levels, and dry conditions of boundary and semiconfining-unit head (from Torak and others, 1996).

site in sign from, the pumpage change used to simulate half of the October 1986 pumpage, depicted on fig. 25. The pattern and magnitude of drawdown shown on figure 43 are nearly identical to the pattern and magnitude of ground-water-level change shown on figure 25, indicating that the Upper Floridan aquifer responds linearly and identically to pumpage changes of equal magnitude but opposite sign. This linear aquifer behavior attests to the reversibility of aquifer response to pumpage, that is, the reference condition of ground-water levels for October 1986, upon which water-level changes are computed, can be obtained by either increasing or decreasing pumpage, depending on whether ground-water levels are, respectively, above or below October 1986 levels. The range of pumpage throughout which this linear aquifer behavior seems to apply is from about 237 Mgal/d to about 712 Mgal/d, or a 3-fold increase in simulated pumpage from rates that are one-half of the October 1986 rate. However, similar linear relations were shown to exist between simulations using one-half and twice ($n=2$) the October 1986 pumping rates (figs. 25, 31), thus extending the upper limit of the range of pumpage over which linear aquifer behavior seems to apply to about 949 Mgal/d.

Comparison of water-level-change maps for simulations using multiples of 0.5 and 5 times the October 1986 pumpage (figs. 25 and 32, respectively) indicates that the Upper Floridan aquifer responds linearly to pumpage increases and decreases over large parts of the study area. In this comparison, pumpage ranges from about 237 to 2,375 Mgal/d, or an order of magnitude, with the larger pumping rate being equivalent to expected pumpage during the height of the growing season. Assuming linear aquifer response to pumpage, water-level change resulting from the higher pumpage would be about 8 times larger than water-level change obtained from the lower pumpage, as the change in pumpage is 8 times larger for the multiple of 5 times the October 1986 pumpage ($n=5$, or 1,900 Mgal/d) than for the 0.5 multiple ($n=0.5$, or 237 Mgal/d). This linear aquifer response to pumpage seems to hold for most of the study area, except where closed contours of water-level change indicated that aquifer dewatering would occur for the larger pumpage, namely in Lee and Miller Counties, Ga., defined, respectively, by the minus-80- and minus-60-ft-water-level change contours (fig. 32). Therefore, in the absence of aquifer dewatering, response of the Upper Floridan aquifer to simulated pumpage is, for the most part, linear, producing predictable patterns of water-level change over about an order-of-magnitude range in pumping rate.

Intermediate system

Ground-water-level change in water-bearing units of the Intermediate system was minimal in response to simulated changes in boundary conditions and stream stage. Variations in stream stage from October 1986 to Q_{50} conditions of less than 5 ft for most streams, and the relative insensitivity of computed head in the calibrated Intermediate model to changes in stream stage and boundary head (Torak and others 1994), resulted in ground-water-level changes of commonly less than 1 ft (figs. 44–48, at the end of this report, p. 136–140). Maximum ground-water-level change of about 4 ft was exhibited by simulating an increase in stream stage from October 1986 to Q_{50} levels (figs. 44, 45); this change occurred in a narrow band near the Apalachicola River in the northern part of the model area. The effect of simulating changes to boundary conditions from dry to normal on ground-water-levels was negligible; only a slight enlarging of areas enclosed by equal water-level-change contours larger than 1 ft occurred in the northern part of the model area. Increasing stream stage from October 1986 to Q_{90} levels created about one-fourth the ground-water-level change created by higher, Q_{50} levels; about 0.5 ft of increase to ground-water levels occurred under Q_{90} conditions in areas where 2 ft of water-level increase was simulated under Q_{50} conditions. Similarly, areas that exhibited 4 ft of ground-water-level increase under Q_{50} conditions experienced a 1 ft increase in ground-water levels for Q_{90} conditions.

Damped simulated response of ground-water levels to changes in boundary conditions in the Intermediate system, including stream stage, coupled with minimal development of ground-water resources and less transmissive aquifer properties than the underlying Upper Floridan aquifer, makes the Intermediate system a hydrologic unit that contains limited ground-water resources. Simulations performed in this study and in Torak and others (1996) involving changes to lateral- and vertical-boundary head indicate that the Intermediate system functions as an ‘intermediate’ hydrologic unit between overlying terrace and undifferentiated

(surficial) deposits and the underlying Upper Floridan aquifer, receiving and transmitting ground water as a function of vertical-leakage components. Although insensitive to head changes along vertical boundaries, which are small in comparison to similar changes in the Upper Floridan model, ground water in the Intermediate system is somewhat regulated by them. As such, changes to head in the overlying surficial deposits (through changes in stream stage), and in the underlying Upper Floridan aquifer, can affect ground-water resources of the Intermediate system.

Accuracy of Results

Errors associated with measuring and reporting hydraulic head and flow properties, well-pumping rates, and stream stage and discharge are termed measurement error. Of all possible sources of error, measurement error is the least consistent in magnitude and often is neglected or ignored; yet measurement error probably has the most influence on evaluating true flow-system behavior. Without an analysis of measurement error, simulation results cannot be interpreted accurately, and flow-system concepts can be obscured.

As described in Torak and others (1996), discrepancies (errors) exist between computed results of calibrated models and measurements of water-level altitude and stream-aquifer flow. Errors in computed results are compounded by inaccurate land-surface altitude data at well locations, and by well-measuring points and ground water levels that are known only to within about half a contour interval of altitude, or, about 5 ft. Inaccuracies in computed stream-aquifer flow are related directly to measurement errors associated with water level, streamflow, and land-surface altitude. The magnitude of error in stream-aquifer flow is equivalent to the range in flow values that result from the range of acceptable values for these measurements.

Simulations performed by Torak and others (1996), using the maximum range in acceptable values for streamflow and water levels resulted in a 394 Mgal/d discrepancy between computed and 'measured' stream-aquifer flow for the reach of the Flint River between Albany and Newton, Ga. This value is about an order-of-magnitude larger than the difference between computed and measured aquifer discharge to the river (38 Mgal/d) obtained with the calibrated model; thus, measurement error can more than compensate for differences between computed and measured stream-aquifer flow. Although other stream reaches contribute much less to the flow system than discharge to the Flint River at this location, measurement error still affects the comparison of computed stream-aquifer flow with measured or estimated flows. For small streams, errors associated with measurements might permit the direction of stream-aquifer flow to be reversed, changing the conceptualization of the flow system and evaluation of water resources for the system.

Transient Response of Flow System to Pumpage Changes

Flow-system response to changes in pumpage and the time needed to achieve steady state is affected by storage properties of the aquifers (storage coefficient and specific yield) and semiconfining units (specific storage). Storage effects cause an unsteady, or transient, flow-system response, characterized by changes to water levels, hydraulic gradients, and flow rates that gradually diminish with time. If the storage properties are zero, then there is no transient flow-system response, and equilibration to a new steady-state condition is instantaneous. However, the flow system of interest contains nonzero-storage properties, which causes a delay in equilibration to a new steady-state condition due to the release or uptake of water by the porous media. Given time, the transient response diminishes to a level beyond all practical considerations, and the flow system is regarded as having achieved a new steady-state condition. The delay in the flow system to achieve steady-state following a pumpage change is termed the time lag.

Transient response of the aquifer-stream-reservoir system to simulated changes in October 1986 pumping rates was analyzed by defining the time lag for the system to achieve a new steady-state condition following a pumpage change. Steady-state conditions of October 1986 were used as a starting point for nonsteady-state (transient) simulations in which pumpage was instantaneously reduced to zero and held constant. Equilibration of the flow system to steady state was measured by the ability of the transient simulation to compute

stream-aquifer flows that corresponded to similar flows obtained from a reference, steady-state simulation of zero pumpage, defined as simulation R1P0 (table 1). The time lag was defined as the simulated time required for the transient simulation to produce stream-aquifer flows that are equivalent to flows obtained from the reference simulation. Stream-aquifer flows for the reference simulation are listed in table 10 as "Discharge to streams and in-channel springs" for October 1986 stream-stage conditions. Because pumpage was negligible in the Intermediate model, only the Upper Floridan model was used in the transient analysis.

The dependence of transient flow-system response on values of the storage properties in the aquifer and overlying semiconfining units poses practical limitations on simulations designed to analyze the time lag of the flow system to achieve steady state following a pumpage change. In a flow system containing nonzero-valued storage properties, true steady-state conditions are achieved only at times that approach 'infinity,' which is purely a theoretical and mathematical exigency. Therefore, a criterion was established that defines the time lag as the simulated time required for computed stream-aquifer flows to reach 97 percent of the values corresponding to the reference, steady-state conditions of simulation R1P0. Storage-property values were changed over plausible ranges and used in transient simulations to obtain a range for the time lag that might be expected for the flow system to meet this criterion.

Transient simulations indicate that the flow system responds nearly instantaneously to pumpage change; however, equilibration to a new steady-state condition occurs after about 100 to 1,000 days (fig. 49; table 34). That is, although transient response to the new, zero-pumpage condition by stream-aquifer flows is nearly instantaneous, a time lag ranging over an order of magnitude (100 to 1,000 days) is needed for flows to satisfy the 97-percent-recovery criterion; the length of the time lag depends on actual values of storage properties in the aquifer and overlying semiconfining units. The largest time lag is associated with the largest values of storage properties, and, similarly, the smallest time lag is associated with the smallest values of storage properties, used in the transient simulations (table 34).

Plots showing percent of steady-state, stream-aquifer flow with time (fig. 49) indicate that transient response of the flow system to pumpage change diminishes in time as steady-state conditions are approached. Continuously decreasing slopes of the "transient-response curves" define a decreased rate of recovery of the flow system with increased time since the pumpage change, until the curves are nearly horizontal as the steady-state criterion is reached. Recovery of less than 97 percent of the steady-state, zero-pumpage, stream-aquifer flows occurs at times that are less than the time lags exhibited by the simulations. The consistent shapes of the transient-response curves indicate that each successive increment of a fixed percentage of recovery takes progressively longer to attain than the previous increment; however, the range in time to achieve a specific percentage of recovery spans an order of magnitude. For example, the transient-response curves on figure 49 indicate that recovery of steady-state flows by 25-percent increments occurs over the following order-of-magnitude ranges in times:

Percent recovery	Time range (days)
25	1.5–15
50	6– 60
75	27– 270

Two observations are noted from results of the transient simulations and time-lag determination concerning the Upper Floridan aquifer and flow system in general. First, steady-state conditions are achieved only if pumping rates (and other hydrologic stresses) are held constant for at least as long as the time lag of 100 to 1,000 days. Second, pumping rates that either change more frequently than, or are not maintained as long as, the time lag will produce transient changes in stream-aquifer flows that are of less magnitude than the total change indicated by a flow system that has achieved steady state with regard to the changed pumpage. Because both issues are related to the duration and temporal distribution of pumpage, their implications to the study area are discussed simultaneously below.

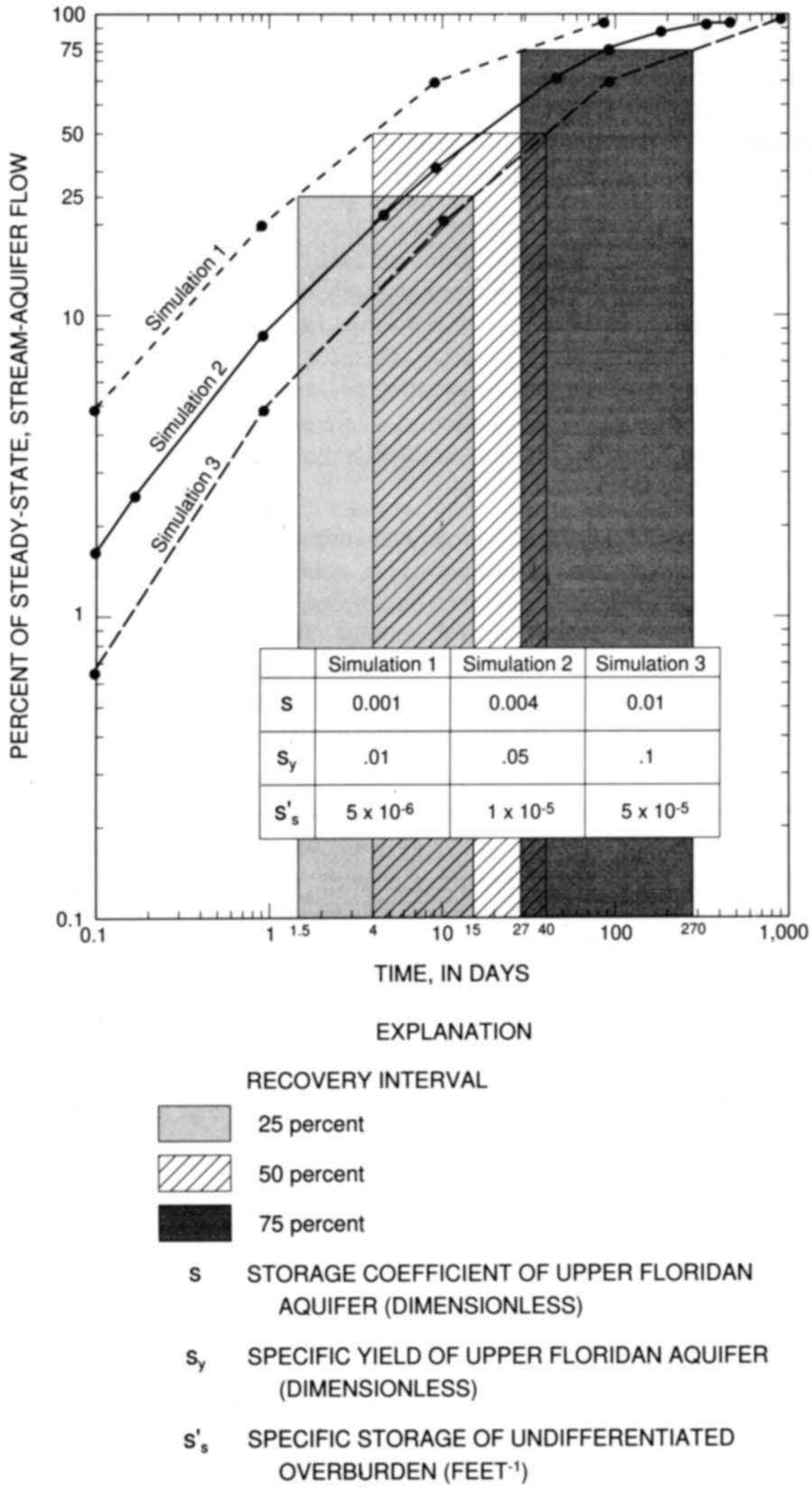

Figure 49. Percent of steady-state stream-aquifer flow attained with elapsed simulation time.

Table 34. Simulated temporal recovery of stream-aquifer flow decline in Upper Floridan model following reduction in October 1986 pumpage to zero
[–, temporal conditions not simulated]

Time since pumpage reduction (days)	Percent recovery[1] of stream-aquifer flux by simulated storage conditions		
	S^2 0.001	0.004	0.01
	$S_y{}^3$ 0.01	0.05	0.1
	$S_s'^4$ 5x10 -6	$1x10^{-5}$	$5x10^{-5}$
0.1	4.98	1.66	0.64
.18	–	2.59	–
1	21.38	8.84	4.98
5	–	22.62	–
10	62.57	31.97	21.38
50	–	63.61	–
100	97.13	79.01	62.57
200	–	90.82	–
365	–	95.9	–
500	–	97.2	–
1,000	–	–	97.13
Steady	100	100	100

[1] Percent recovery is simulated recovery of stream-aquifer-flux decline at elapsed time since pumpage was set to zero, divided by total recovery of stream-aquifer-flux decline for simulated, steady-state, zero-pumpage conditions, multiplied by 100. Recovery is based on reduction of October 1986 pumpage of 475 million gallons per day (Mgal/d) and total recovery at steady state of 289.8 Mgal/d.

[2] Storage coefficient of Upper Floridan aquifer (dimensionless).

[3] Specific yield of Upper Floridan aquifer (dimensionless).

[4] Specific storage of undifferentiated overburden ($feet^{-1}$).

A time lag of the range 100 to 1,000 days for the flow system to equilibrate to pumpage change in the Upper Floridan aquifer indicates that typical seasonal pumping rates vary too frequently in time for the flow system to achieve steady state with regard to a specific pumping rate. Irrigation pumpage is dominated by seasonal and daily crop demands for water; thus, during a growing season, it is highly unlikely that pumping rates are held constant for months, weeks, or even days at a time. Hence, during a growing season, the flow-system probably is adjusting continually to short-term increases and decreases in pumpage. The effects of “unresolved” antecedent pumpage changes on the flow system increase the complexity of the transient response from that indicated by the curves shown in figure 49. Consequently, only a percentage of the total change in stream-aquifer flows from the previous steady-state condition to a new steady-state condition, reflecting current pumping rates, might actually be realized by the flow system.

The percent of total change in stream-aquifer flows resulting from a short-term-pumpage change (duration less than the time lag for achieving steady state) can be computed by using the transient-response curves (fig. 49) and knowledge about the duration of the new pumping rate. For example, low streamflow and high pumpage are short-term events that probably will not coincide for more than 30 to 60 days at the end of a growing season. High pumpage might correspond to rates that are 2 or 5 times the October 1986 rates, and low streamflow might correspond to flows for stream stages at October 1986 or Q_{90} levels. From the re-

sponse curve (fig. 49), the percent of total change in stream-aquifer flows expected to occur during the time in which low streamflow and high pumpage coincide (30 to 60 days) ranges from about 75 to 85 percent for Simulation 1, and about 32 to 50 percent for Simulation 3; the bounds for each simulation are the percentages that correspond to the 30- and 60-day time in which these hydrologic conditions coincide. Therefore, if low streamflow and high pumpage are maintained at constant levels for 30 days, then about 32 to 75 percent of the total change in stream-aquifer flows might be expected to occur, as defined by the range of the lower bounds of transient responses for Simulations 1 and 3. Similarly, if these conditions are maintained for 60 days, then about 50 to 85 percent of the total change in stream-aquifer flows might be expected to occur, as defined by the upper bounds of the transient responses for Simulations 1 and 3. Net changes to stream-aquifer flows from initial conditions of zero pumpage and low streamflow are given in tables 14–17, and are listed as "Reduced discharge to streams and in-channel springs" and as "Induced recharge from springs."

As inferred from the above example, results of the time-lag analysis can be applied to hydrologic conditions other than those of October 1986. Because the flow-system exhibits linear response for the range of hydrologic conditions under which the time-lag analysis was performed, results of the analysis can be applied to the hydrologic conditions listed in the simulation matrix of table 1 that also elicited linear responses from the flow system. For example, the curves in figure 49 can be used to describe transient response of the flow system to simulated combinations of pumpage at 0.5 and 2 times the October 1986 rates, ground-water levels for lateral and vertical boundary conditions at normal levels, and stream stage at Q_{50} or Q_{90} levels. Because pumpage at 5 times the October 1986 rates might cause parts of the Upper Floridan aquifer and some streams to go dry, discussed previously, flow-system linearity, and transient-response curves in figure 49, would not apply locally in the vicinity of these drying conditions. However, for most hydrologic conditions listed in table 1, transient response of the flow system to pumpage change is described by the above time-lag analysis and transient-response curves in figure 49.

Although transient response of the aquifer to pumpage change is nearly instantaneous, the response of stream-aquifer flows is neither instantaneous nor identical for every stream or stream reach in the study area. Each stream or stream reach exhibits a unique transient response to pumpage change and possesses a distinct lag time to achieve steady state, depending on proximity to pumped wells (thus, proximity to computed head changes) and size and geometry of sub-basin drainage areas. Effects of these hydrologic characteristics are indicated by comparing temporal variations in computed net stream-aquifer flow for 37 stream reaches in the basin (table 35) with locations of nodes simulating pumpage (pl. 8), following a pumpage change to zero. Larger sub-basins take longer to equilibrate than smaller sub-basins as more aquifer material is involved in the transient response of stream-aquifer flow to pumpage change. Similarly, wells located far from streams (or specific reaches) will elicit a transient response in more aquifer material, thus requiring a longer time lag for equilibration, than wells located close to streams. The magnitude of change in stream-aquifer-flow caused by variations in pumping rates differs by stream or reach according to the amount of pumpage change in the corresponding sub-basin.

Transient response of specific stream reaches to pumpage change (table 35) indicates that the actual change in stream-aquifer flows caused by temporal variation of pumpage during a typical growing season probably is less than the change indicated by the flow system at steady state (tables 20–25). For example, for reach 31 (Flint River, plate 9), a simulated decrease in pumpage to zero for 10 days causes an increase in computed net stream-aquifer flow (aquifer discharge to stream) of 32.5 ft^3/s (637.5 minus 605 ft^3/s, table 35). However, the total change in aquifer discharge after 100 days, when the flow system achieves steady state, is 46.7 ft^3/s. Aquifer discharge along the reach 10 days after the pumpage change is about 70 percent of the total change that might be expected to occur once the flow system achieves steady state. The 70-percent value is unique to reach 31, because transient response to pumpage change differs for other reaches. For example, the change in aquifer discharge to reach 1 (Gum Creek) after 10 days is only 27 percent of the total change in discharge that might occur once steady state is achieved. Therefore, the curves in figure 49 represent transient response of stream-aquifer flows to pumpage change for the flow system as a whole; individual streams and reaches exhibit unique transient response, which differs from the response shown in figure 49.

Table 35. Temporal recovery of stream-aquifer-flow decline by stream reach following simulated reduction in October 1986 pumpage to zero—results from Simulation 2 of Upper Floridan model

[Storage coefficient and specific yield of Upper Floridan aquifer equal 0.004 and 0.05, respectively; specific, storage of overlying semiconfining unit equals 1x10^{-5} feet^{-1}; negative values indicate losing stream]

Reach (pl. 4)	Stream	Elapsed simulation time since pumpage decrease (days)			
		0	1	10	100
		Computed net stream-aquifer flow (cubic feet per second)			
1	Gum Creek	3.6	3.6	3.9	4.7
2	Cedar Creek	1.3	1.3	1.3	1.4
3	Swift Creek	3.8	3.8	3.8	4
4	Jones Creek	2.3	2.3	2.3	2.4
5	Abrams Creek	2.6	2.6	2.7	2.9
6	Mill Creek	6.9	6.9	7	7.4
7	Coolewahee Creek	.5	0.5	.8	1
8	Chickasawhatchee Creek	4.1	4.1	4.1	4.1
9	Chickasawhatchee Creek	.3	.3	.3	.4
10	Chickasawhatchee Creek	2.8	2.8	3.1	3.4
11	Dry Creek (Ga.)	2.8	2.8	2.9	3.3
12	Spring Creek	3.5	3.5	3.7	4.1
13	Spring Creek	19.5	19.9	22.5	28.4
14	Spring Creek	1.1	1.2	2	6.7
15	Sawhatchee Creek	9.6	9.6	9.6	9.8
16	Cowarts Creek	19.9	19.9	19.9	20
17	Marshall Creek	31.6	31.6	31.6	31.7
18	Spring Creek	42.2	42.4	45.6	60.1
19	Dry Creek (Fla.)	42.1	42.1	42.1	42.2
20	Ichawaynochaway Creek	52.6	52.7	53.2	54.3
21	Ichawaynochaway Creek	23.7	23.7	24.1	24.8
22	Muckalee Creek	17.8	17.8	17.9	19.6
23	Muckalee Creek	3.9	3.9	3.9	4.1
24	Muckalee Creek	14.2	14.2	14.3	14.7
25	Kinchafoonee Creek	-2.3	-2.3	-2.3	-2.3
26	Kinchafoonee Creek	5.9	5.9	6	6.3
27	Chipola River	114.7	114.7	114.8	115.2
28	Chipola River	339.6	339.6	339.6	339.9
29	Chipola River	359.2	359.2	359.3	359.3
30	Flint River	6.3	6.3	6.4	6.5
31	Flint River	605	622.2	637.5	651.7
32	Flint River	537.3	545	569	589.5
33	Flint River	363.5	365.1	376.3	414.1
34	Flint River	352.2	353.8	371.2	416
35	Apalachicola River	281.6	281.8	282.2	282.6
36	Apalachicola River	165.5	165.6	165.8	165.9
37	Apalachicola River	522.8	522.8	522.8	522.8

A linear flow system allows transient responses to frequent pumpage change to be analyzed by superposing transient-response curves and time lags for successive changes. The initial transient-response curve (initial time lag) for an initial pumpage change is augmented by superposing a similar curve at the point in time corresponding to the new pumpage change. Additional pumpage changes generate transient-response curves that are combined with the previous composite curve, which results in lengthening the time lag to achieve steady state. Equilibration of the flow system to many pumpage changes takes longer than one time lag; such is the case during a growing season, when pumpage changes occur monthly, weekly, or even daily.

Depending on the temporal distribution of seasonal pumpage, transient conditions might exist year round, as pumpage for a new growing season might be initiated before the flow system equilibrates to the cessation of pumpage from the previous season. Changes to boundary conditions, either lateral or vertical,

create their own transient conditions and response times for equilibration of the flow system. The apparent steady-state condition exhibited by the flow system for October 1986 probably is the result of a unique combination of hydrologic factors: climate (drought), hydrologic stress (decreased pumpage at the end of the growing season), and changes to boundary conditions, which caused static water levels in the study area for a brief time. The transient response of stream-aquifer flows to pumpage requires that a constant level of hydrologic stress (such as pumpage) be maintained for a period of time that is longer than typical seasonal-pumpage cycles.

Results of the time-lag analysis indicate that true flow-system response to pumpage is a complex process involving adjustment of flow-system parameters other than ground-water levels and stream-aquifer flows. The length and duration of time lags are not only dependent on knowledge of storage properties of the Upper Floridan aquifer and overlying semiconfining units, but involve complex interactions of ground-water flow with lateral and vertical boundary conditions. Changes in these conditions and in other stresses during the time lag interfere with flow-system adjustments to pumpage change, making observation or verification of simulated lags difficult, if not impossible. For this reason, aquifer adjustment to pumpage change, such as changes to ground-water levels, can persist long after stream-aquifer flows seem to have equilibrated.

The equilibration of stream-aquifer flows to near-steady-state conditions within a relatively short time period indicates that ground-water levels in the vicinity of streams approach steady state relatively quickly compared with aquifer conditions that still might be changing upgradient of the streams. Spatial and temporal changes in aquifer thickness and in vertical-leakage rates in the vicinity of pumped wells located away from streams create transient effects on ground-water-flow patterns and boundary conditions. Multiple wells cause complex boundary flows and interference patterns in the potentiometric surface that require time to resolve during equilibration. Thus, the process of achieving steady state in the Upper Floridan aquifer is more complex for ground-water levels and requires longer time than for stream-aquifer flows.

Potential for Changes to Water Quality

The potential for changes in chemical quality of water in the aquifer-stream-reservoir system can be determined by evaluating hydraulic mechanisms controlling ground-water flow and land use. The hydraulic mechanisms are vertical leakage from underlying and overlying hydrologic units, leakage across sediments connected to surface-water features, regional inflow across study-area boundaries, and recharge from outcrop areas. Changes to hydraulic characteristics of the flow system that cause these mechanisms to operate in the study area also affect water quality; therefore, water quality is related to changes in hydraulic head and hydraulic conductivity of aquifers and semiconfining units, surface water levels, and pumpage in the Upper Floridan aquifer. Land use is discussed later in this section.

Water-budget components from steady-state simulations indicate that ground-water recharge by vertical leakage and regional flow has the greatest potential to change water quality in the Upper Floridan aquifer (tables 10–19). Vertical leakage from the overlying semiconfining unit of the undifferentiated overburden provides the most water to the aquifer. Under zero-pumpage conditions, ground water enters the aquifer from the undifferentiated overburden at about 5 times the October 1986 pumping rate. For variable-pumpage scenarios, the leakage rate increases in proportion to pumpage; about 20 to 35 percent of the pumped water is induced recharge from the overburden. For zero-pumpage conditions, regional flow recharges the Upper Floridan aquifer at about 40 percent of the rate supplied by vertical leakage, and an additional 5 to 6 percent of the pumping rate is induced recharge across lateral boundaries for the pumpage scenarios. Potential water-quality changes in the Upper Floridan aquifer by vertical leakage from the undifferentiated overburden can occur in areas where the overburden is subject to contamination from surface sources, such as industry, agriculture, and surface-water runoff; thus, potential changes to water quality are not limited to outcrop areas of the aquifer. In fact, the effect of recharge from outcrop areas on changing water quality is slight, because this source of water supplies less than 3 percent of total recharge under nonpumped conditions and less than 2 percent of the pumping rates.

For the Intermediate system, recharge by leakage from the underlying Upper Floridan aquifer and overlying semiconfining unit, and by regional flow provide the greatest potential to change water quality. In most scenarios of dry and normal boundary conditions and stream-stage variation, upward leakage into the Intermediate system from the Upper Floridan aquifer supplied most of the recharge water (tables 12, 13). Recharge from overlying deposits and regional flow provide nearly equal amounts of water to the Intermediate system, and share an equal potential to change water quality.

Discharge mechanisms of the Upper Floridan aquifer and Intermediate system also can change water quality in semiconfining units and surface-water features. In the Upper Floridan aquifer, discharge to streams is the largest discharge component, comprising about 75 to 85 percent of total discharge under zero-pumpage scenarios. For pumpage scenarios, ground-water discharge to streams is reduced in proportion to the pumping rate; about 55 to 60 percent of pumpage is water diverted from discharge to streams. Because ground-water discharge to streams occurs along almost every reach for each pumpage scenario, there is great potential for surface-water quality to be affected by ground water. Conversely, ground-water discharge to streams computed for the pumpage scenarios implies that ground-water quality is affected only slightly by surface water, as hydraulic gradients across streambeds are such that only aquifer discharge across streambeds occurs. Also, in the vicinity of streams, ground water discharges upward from the Upper Floridan aquifer to semiconfining units. Here the potential for upward-vertical leakage from the aquifer to change water quality in the overlying semiconfining units is great, and the potential for leakage across streambeds into these units is slight, because this flow would be against prevailing hydraulic gradients.

The Intermediate system can affect water quality in streams and in the Upper Floridan aquifer through ground-water discharge across streambeds and downward-vertical leakage, respectively. About 85 percent of total discharge from the Intermediate system is leakage to the Upper Floridan aquifer and to stream-aquifer flow; hence the potential for the Intermediate system to affect water quality in streams and in the Upper Floridan aquifer is presumed to be great. The remaining ground-water discharge occurs as regional flow and discharge to the overlying semiconfining unit, and is small in comparison with downward leakage and stream-aquifer flow. Therefore, the potential for the Intermediate system to cause changes in water quality outside of the study area and in the overlying semiconfining unit is slight.

Although hydraulic mechanisms can be evaluated to determine the potential to change water quality, the most influential and perhaps unpredictable element to cause water-quality change in the study area is man. Planned or unplanned surface application of chemicals, leaky underground-storage tanks, discharge of treated or untreated effluent and industrial waste into surface and ground waters, and the hydrologic consequences of acid deposition increase the potential to change water quality. Areas where semiconfining units are thin or absent, where vertical leakage into aquifers is direct from the surface or through surficial deposits, and where streams recharge the aquifers can be regarded as areas of high potential for change in ground-water quality, given man's intervention. The proximity of industry to surface water poses a potential for change in ground- and surface-water quality. Introduction of these anthropogenic factors locally into the aquifer-stream-reservoir system increases the potential to change water quality as hydraulic mechanisms function to define the hydrodynamics of the basin.

Ground-Water-Development Potential

Ground-water-development potential in the ACF River Basin reflects, in part, an assessment of the cumulative effects of current and future hydrologic stresses imposed on the flow system that influence the area under investigation. The nature of the assessment limits its scope and range of application. Current hydrologic conditions might be unacceptable for use as the standard upon which effects of additional stress and development potential are evaluated. Because current stresses and hydrologic conditions might be unknown in some areas, and uncertain in others, evaluation of development potential based on such tenuous knowledge would be meaningless. Future stresses might be linked to water-management practices that have yet to be

formulated, or to water-management decisions that have yet to be made. Therefore, an assessment of ground-water-development potential can give insight only into one aspect of the broader issue of how management decisions can affect ground-water availability; specifically, whether existing hydrologic data can document flow-system behavior adequately to allow quantification of the potential effects of future development. Further, this assessment is not intended to give definitive answers regarding the acceptability of the effects of current ground-water use or the potential for further resource development. Such decisions require synthesis of results from other Comprehensive Study components and subsequent consideration by the responsible parties in the basin.

Evaluation of the development potential of ground-water resources in the Upper Floridan aquifer presupposes that adequate information is known everywhere about the flow system and its behavior to permit such a 'hydrologic inventory' or an 'audit' to be made. Although a wealth of information exists in some parts of the study area to allow detailed hydrologic characterization, other, larger parts of the study area were characterized in a general manner by using sparse data and estimates, and by extrapolating information from areas where more plentiful data are available. To make subjective management decisions about where to develop or conserve ground-water resources on the basis of sparse hydrogeologic data or simulation results derived from unsubstantiated estimates of hydraulic properties and stresses is problematic. However, some useful insights concerning development potential of ground-water resources can be gained from the somewhat conservative evaluation of available hydrologic information and subsequent analysis of simulation results that follows.

Evaluation of development potential of ground-water resources in the Upper Floridan aquifer is affected by the spatial distribution of hydrologic data in the study area and by pumpage; two factors that are determined by well distribution. Well distribution limits the evaluation to areas where sufficient data exist to support either hydrologic characterization and inference or the development of cause-and-effect relations of pumpage on the flow system. Because pumpage in the Upper Floridan aquifer is not evenly distributed throughout the study area, the effects of increased pumpage are likewise neither evenly distributed nor equitably monitored. Because pumpage in the Intermediate system is virtually nonexistent, the development potential of its ground-water resources will remain unknown until enough hydrologic information is collected to adequately characterize the water-bearing units, and until these units are stressed appreciably by pumpage. Thus, development potential cannot be evaluated with the same level of detail everywhere in the study area. Broad generalizations about the potential to increase pumpage in specific areas cannot be made unequivocally on the basis of well distribution alone, even though the effect of increased pumpage on the flow system seems to be greatest in areas having the largest concentration of wells and least where wells are few and widely spaced. This is not to say that areas containing either abundant or sparse well distributions will possess a higher or lower potential for increased pumpage than other areas, or that an area of sparsely distributed wells has less potential for development than another area that is highly populated with wells.

Development potential of ground-water resources in the Upper Floridan aquifer is evaluated with regard to the ability of the flow system to sustain pumpage in specific areas and experience minimum or no unfavorable effects on the aquifer and surface-water features. The evaluation is tempered by the extent to which specific criteria are met to detect pumpage-induced effects on the flow system; these criteria utilize water-level and streamflow measurements or other physical means to analyze pumpage effects. Although the availability and distribution of data precludes evaluation of each criterion everywhere, there is enough information in some areas so that evaluation of some criteria make the evaluation of others superfluous to the development potential issue. Similarly, evaluation of each criterion, even in the presence of available data, might be unnecessary if any one criterion is met to a large degree. One measure of development potential is the capacity of the aquifer to meet the demand of increased pumpage with minimum water-level decline. Other measures evaluate development potential on the basis of the effects of pumpage on the flow system as measured by baseflow reduction of streams and percent reduction of total streamflow leaving the study area to discharge to Apalachicola Bay. These are the 3 most apparent and easily measurable effects of increased pumpage on the flow system and constitute the basis for evaluating ground-water-development potential. Specific

areas are classified as possessing high or low development potential depending on the extent to which any or all of these criteria are fulfilled.

To the extent that present monitoring and simulation results allow, development potential of ground-water resources in the Upper Floridan aquifer was classified as low in a specific area depending on the degree to which any or all of the following pumpage-induced effects were simulated:

- Complete dewatering of the Upper Floridan aquifer
- Water levels in wells drop below pump intakes
- Dewatering of karstic sections of the Upper Floridan aquifer
- Large reductions in aquifer discharge to streams (stream-aquifer flow), stream reaches go dry, or streams transform from gaining to losing
- Reduction in streamflow to the Apalachicola River and Bay, especially during low-flow periods such as droughts

Development potential of ground-water resources in the Upper Floridan aquifer was classified as high if any or all of the simulated, pumpage-induced effects listed above were nonexistent or inconsequential to the flow system.

Simulation results and hydrologic data were used to make inferences about the development potential of ground-water resources in specific areas according to the above criteria. General areas where the aquifer has been completely dewatered as a result of pumpage can be delineated by comparing the map of aquifer thickness (pl. 3) with water-level-change maps showing the combined effects of pumpage, boundary conditions, and stream stage on the Upper Floridan aquifer (figs. 25–42). Changes to stream-aquifer flows for specific reaches (tables 20–25) indicate the local effect of simulated pumpage and boundary conditions on aquifer discharge to streams, stream recharge to the aquifer, and reaches that transform from gaining to losing. Well-construction details and site-specific information about karstic features in the Upper Floridan aquifer were compiled for this study from previous investigations (Hicks and others, 1987; Torak and others, 1993, 1996) and were used to define, qualitatively, zones of hydraulic conductivity for the Upper Floridan model (pl. 6). Additional work is needed on a site-specific basis to quantitatively evaluate the effect of increased pumpage on known karstic features, and whether simulated water-level declines would lower the potentiometric surface below existing pump intakes.

On the basis of the above criteria, there is a low potential for development of ground water from the Upper Floridan aquifer in parts of the northern half of the model area, where the aquifer is thin and effects of current pumpage on the flow system are large and well documented by measurements of ground-water level and streamflow. Areas north of Lake Seminole in Baker, Crisp, Lee, and Miller Counties, Ga., sustain large amounts of pumpage and pumpage-induced, ground-water-level and stream-aquifer-flow decline, as evidenced in corresponding illustrations and tables presented previously. Aquifer dewatering was simulated in some of these areas for pumpage at 5 times the October 1986 rates.

Areas that exhibit high potential for development of ground water from the Upper Floridan aquifer are located in Decatur, Dougherty, Worth, and northern Baker and Mitchell Counties, Ga., and in Alabama and Florida, where increased pumpage from the October 1986 rates caused minimal ground-water-level decline. In these areas, the Upper Floridan aquifer has the capacity to transmit large quantities of water to surface-water features and incur minimal effects of pumpage. A detailed investigation of the effects of pumpage on the stream-aquifer system comprised of the Upper Floridan aquifer and Flint River in the Albany, Ga., area (Torak and others, 1993) defined zones of high aquifer transmissivity related to solution (karstic) features in the Upper Floridan aquifer that were responsible for conveying large quantities of water to springs, wells, and the Flint River. In that study, simulations of increased pumpage in an area of potential ground-water development indicated that karstic features were not affected by pumpage increases, and that pumpage-induced changes in streamflow were minimal.

Despite the appearance that ground-water levels are virtually unaffected by pumpage in areas of Alabama and Florida, the sparse distribution of pumped wells and available water-level data in these areas for October 1986 (Thomas R. Pratt, Northwest Florida Water Management District, oral commun., 1993), requires further examination and analysis before development potential can be evaluated. Because pumpage from only a few wells in Alabama and Florida were simulated with the Upper Floridan model, only minimal effects of pumpage were exhibited, and can be expected, from pumpage increases applied to the presently known well distribution. In Florida, the Upper Floridan aquifer ranges in thickness from about 100 to more than 500 ft and has moderate levels of hydraulic conductivity. Therefore, it is unlikely that the aquifer would either experience dewatering or discharge noticeably less water to streams due to increased pumpage from a more dense well distribution than is contained in the model. In contrast, the aquifer thins to less than 50 ft in Alabama; there, increased pumpage can cause noticeable dewatering and stream-aquifer-flow declines. A more accurate and meaningful evaluation of development potential for pumpage in the Upper Floridan aquifer in Alabama and Florida would involve a detailed inventory of well-construction information, pumping rates, and water levels, and incorporation of these data into the Upper Floridan model, as appropriate.

Broad generalizations about the development potential of ground-water resources in the Upper Floridan aquifer can be inferred from an evaluation of simulated, pumpage-induced, stream-aquifer-flow declines that occur at the headwaters of the Apalachicola River and from pumpage effects on total streamflow that discharges to Apalachicola Bay. Reductions in headwater flow of the Apalachicola River were quantified by subtracting the simulated, pumpage-induced, stream-aquifer-flow declines in streams situated upstream of Chattahoochee, Fla., from streamflow at Chattahoochee, Fla., for October 1986, Q_{90}, and Q_{50} conditions, and expressing the results as a rate and percentage of flow reduction at this location (table 36). Total reductions in flow to the Apalachicola River and Bay were quantified by first adding the simulated, stream-aquifer-flow declines that occurred between Chattahoochee and Sumatra, Fla., to similar declines in headwater flow. Then total declines were subtracted from streamflow at Sumatra, Fla., to produce total-streamflow reductions. Although located about 20.6 miles upstream from the mouth of the Apalachicola River (pl. 1), flow reductions at Sumatra, Fla., represent the entire loss of streamflow to the Apalachicola River and Bay caused by simulated pumpage. No wells are situated near the river downstream from Sumatra, Fla., to cause additional flow reductions, and no other streams that drain pumpage-affected parts of the study area discharge to the Bay.

Reductions in headwater flow of the Apalachicola River are caused by pumpage in the Upper Floridan aquifer that is located upstream from Chattahoochee, Fla. Specifically, simulated pumpage in Houston County, Ala., Jackson County, Fla., and in the entire study area in Georgia (the Dougherty Plain) causes the reductions in headwater flow listed in table 36. This pumpage represents about 99 percent of the total simulated pumpage in the study area, shown on plate 7. Consequently, about 99 percent of the total-streamflow reduction to the Apalachicola River in response to simulated pumpage occurs as decreased headwater flow; the remaining 1-percent-flow reduction occurs as decreased streamflow between Chattahoochee and Sumatra, Fla. (table 36).

Reductions in headwater flow exhibit a nearly linear relation over the ranges in streamflow for October 1986, Q_{90}, and Q_{50} conditions and simulated pumpage (table 36). That is, multiples of simulated pumpage yield nearly the same multiples of streamflow reduction for all streamflow conditions listed in the table. Slight nonlinearities in streamflow reduction are associated with low flows (October 1986 and Q_{90} conditions) and the highest simulated pumping rate; these nonlinearities are discussed later in this section.

Although Q_{90}, and Q_{50} conditions represent statistical flows that were computed for the entire period of record at Chattahoochee, Fla., which began in October 1928, changes in climate and pumpage over this period and the regulation of flow due to filling of Lake Seminole behind Jim Woodruff Lock and Dam (in 1957) do not seem to influence the linear response of the flow system to simulated pumpage. That is, the linear relation of streamflow reduction to pumpage seems to hold for reductions that are applied to specific seasonal conditions, such as October 1986, as well as to statistical flows, which are not representative of any particular season, climate, pumpage, or regulated-flow conditions. However, the magnitude of pumpage-induced-flow reductions is affected by variations in seasonal and statistical streamflows. This is evidenced in table 36

Table 36. Reduction in flow of Apalachicola River at Chattahoochee, Fla., and near Sumatra, Fla., caused by simulated pumpage in Upper Floridan aquifer

[Mgal/d, million gallons per day. Accuracy of streamflow records is "good," except for those at Sumatra, Fla., below 9,695 Mgal/d (15,000 cubic feet per second), which are tide affected and rated "fair." Good means that about 95 percent of the daily discharges are within 10 percent; and fair, within 15 percent]

Pumpage		Streamflow reduction by condition, Q_{nn}					
n x Oct 1986 rates	Rate (Mgal/d)	Q_{OCT86}[1] (Mgal/d)	Percent	Q_{90}[2] (Mgal/d)	Percent	Q_{50}[3] (Mgal/d)	Percent
Apalachicola River at Chattahoochee, Fla.							
0.5	237	142.6	3.7	142.3	2.5	140.4	1.3
1	475	286.9	7.4	286	5	281.8	2.7
2	949	584.2	15.1	581.7	10.1	570.8	5.5
5	2,375	1,263	32.7	1,255	21.8	1,365	13
Apalachicola River at Sumatra, Fla.							
0.5	237	144	3	144	2.2	142	1.1
1	475	290	6.1	289	4.5	284	2.2
2	949	590	12.5	588	9.2	576	4.5
5	2,375	1,276	27	1,268	19.8	1,378	10.8

[1] From pumpage scenarios R1P*n* (table 14); Q_{OCT86} is October 1986 streamflow, equal to 3,864 Mgal/d at Chattahoochee, Fla., and 4,735 Mgal/d near Sumatra, Fla.

[2] From pumpage scenarios R3P*n* (table 16); Q_{90} is streamflow exceeded 90 percent of the time, equal to 5,772 Mgal/d at Chattahoochee, Fla., and 6,392 Mgal/d near Sumatra, Fla.

[3] From pumpage scenarios R6P*n* (table 19); Q_{50} is streamflow exceeded 50 percent of the time, equal to 10,471 Mgal/d at Chattahoochee, Fla., and 12,798 Mgal/d near Sumatra, Fla.

by variations in the percentage of streamflow reduction for October 1986, Q_{90}, and Q_{50} streamflow conditions at each pumpage multiple of the October 1986 rates, and by the linear relations of streamflow reduction to simulated pumpage that seem to hold for each streamflow condition. For example, the maximum percentage of streamflow reduction occurs for the lowest flow condition, October 1986. In general, streamflow reductions for October 1986 conditions are slightly less than about twice the reductions that occur for Q_{90} conditions, and are slightly less than 3 times the reductions for Q_{50} conditions. Further analysis of the effects on headwater flow of temporal variations in seasonal and statistical flows caused by climatic changes, changes in pumpage distribution, and Lake Seminole was not performed and is beyond the scope of this study.

At Sumatra, Fla., the total reduction in streamflow in the Apalachicola River in response to increases in total simulated pumpage in the Upper Floridan aquifer seems to follow a nearly linear relation similar to the pumpage-induced streamflow reductions exhibited at Chattahoochee, Fla. (table 36). However, unlike stream records at Chattahoochee, Fla., the shorter period of record at Sumatra, Fla., from September 1977 to September 1993, indicates that statistical flows representing Q_{90}, and Q_{50} conditions were computed using less climatic variations than at Chattahoochee. In addition, stream records at Sumatra postdate the initiation of irrigation pumpage from the Upper Floridan aquifer; the beginning of the period of record coincides with the year in which annual-irrigation pumpage in the Dougherty Plain of Georgia increased from 47 to 76 billion gallons (Hayes and Maslia, 1983, p. 3). Despite the relatively short period of record at Sumatra, the statistical flows indicate linear-flow-system response to pumpage equally as well as the seasonal flow of October 1986 (table 36). Analysis of whether flow statistics at Sumatra, Fla., have been affected by the advent of pumpage and/or pumpage variations is worthwhile for evaluating the development potential of the Upper Floridan aquifer; however, such an analysis is beyond the scope of the present study.

Aside from temporal changes in streamflow caused by variations in climate and pumpage, tides can affect stage measurements at Sumatra, which subsequently affect streamflow computations and the evaluation of development potential of ground-water resources. Tides could cause fluctuations of about 0.1 ft in measured river stage at Sumatra; thus, stages were corrected for tides before computing Q_{50} and Q_{90} flows (Marvin A. Franklin, U.S. Geological Survey, Tallahassee, Fla., oral communication, February 1995).

The relation of streamflow reduction to increased pumpage is slightly nonlinear for streamflow at October 1986 and Q_{90} levels and pumpage of up to 5 times the October 1986 rates (table 36; fig. 50). For pumpage in the range of 0.5 to 2 times the October 1986 rates, the relation of total-streamflow reduction to pumpage is nearly linear. Previous results obtained from steady-state simulations of increased pumpage indicate similar linearity (and nonlinearity) between pumpage and stream-aquifer-flow reductions (tables 14, 16, 19). The steady-state simulations quantified effects of long-term pumpage on normal (Q_{50}) and low (Q_{90} and October 1986) flows by computing flow rates for aquifer discharge to streams and stream recharge to aquifers for pumpage of up to 5 times the October 1986 rates. The slight nonlinearity in the relation of streamflow reduction to pumpage increase indicated by table 36 and figure 50 can be viewed as an inability of the pumpage multipliers to accurately depict the percentage of long-term-streamflow reduction for the highest simulated pumping rate for October 1986 and Q_{90} conditions. These nonlinearities probably are caused by streams going dry for the combination of long-term-high pumpage and low streamflow. Therefore, development potential of ground-water resources might be limited to short-duration (less than 60 days) occurrences of high pumpage and low flows that do not achieve steady state in the flow system. Short-term pumpage produces transient response, which was shown previously by results of transient simulations to cause less streamflow reduction than the long-term pumpage that achieves steady state.

Reductions in flow of the Apalachicola River near Sumatra, Fla. (table 36; fig. 50), indicate that pumpage effects on total streamflow are relatively small for combinations of pumping rates and streamflows that are most likely to occur simultaneously to produce steady-state conditions. Because conditions of pumpage at 5 times the October 1986 rates and streamflows at either Q_{90} or October 1986 levels are not likely to exist for times that would allow the flow system to achieve steady state (100 to 1,000 days), corresponding flow reductions of 20 to 27 percent, listed in table 36, probably will not be attained. Rather, depending on storage properties in the aquifer, only about 33 to 80 percent of the reductions listed in table 36 for these high-pumpage, low-flow scenarios might be possible, as these conditions might exist for only about a month or two, during which time transient effects would prevail in the flow system. This range for decreasing the percent reductions of total streamflow is derived from figure 49 by using transient effects from Simulation 3 at 30 days and Simulation 1 at 60 days.

Because normal conditions of boundary and semiconfining-unit head usually do not coincide with low streamflows, only values of head that correspond to dry conditions were used in the simulations to compute percent-streamflow reduction for low flows at Q_{90} and October 1986 levels. Conversely, dry conditions for boundary and semiconfining-unit head usually are not associated with Q_{50} flows; thus, flow reductions for Q_{50} levels were computed from simulations that used normal conditions of boundary and semiconfining-unit head. Simulations from the matrix of table 1 that were used to obtain percent reductions of streamflow due to pumpage are listed in the footnotes to table 36.

Assessment of the true ground-water-development potential of the Upper Floridan aquifer requires not only knowledge of anticipated pumpage increases, but also of their duration, prevalent-streamflow conditions, and boundary and semiconfining-unit head at the time in which increased pumpage takes effect. Although pumpage-induced reductions in stream-aquifer flow (aquifer discharge to streams) range from about 53 to 62 percent of the pumping rate (tables 14, 16, 19), the effect of these reductions on total streamflow in the Apalachicola River and on development potential is less for a flow system that exhibits only transient response to changes in hydrologic conditions than for a flow system that achieves steady state. Decreases of about 33 to 80 percent in the reduction of total streamflow, as described above, can be applied to the stream-aquifer flows in tables 14, 16, and 19, to represent transient response of the flow system to short-term changes. Similar decreases to the steady-state, ground-water-level declines depicted on figures 25–42 also might be expected to occur for short-term combinations of pumpage, boundary conditions, and streamflow.

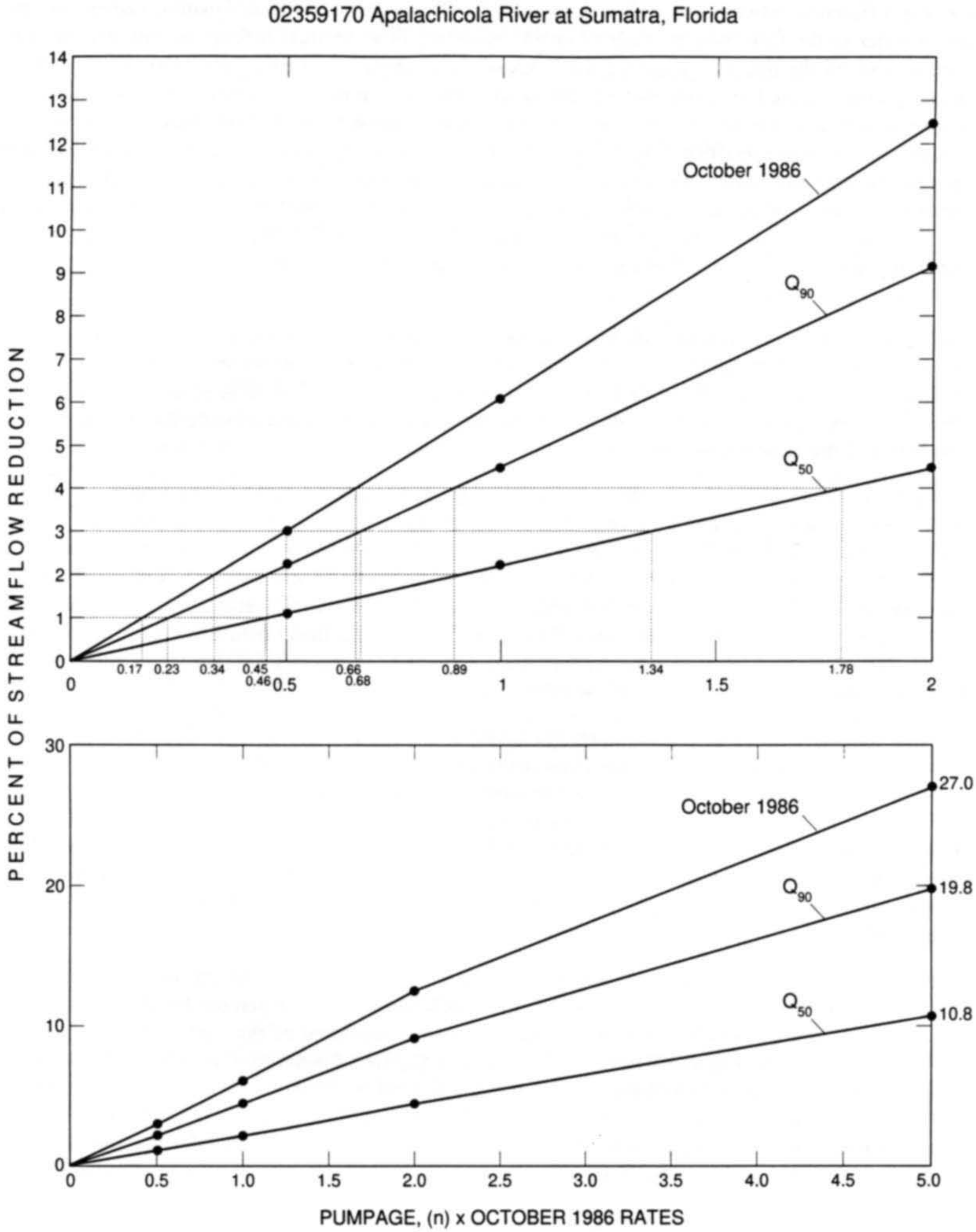

Figure 50. Percent flow reduction of Apalachicola River near Sumatra, Fla., for simulated pumpage scenarios and flows at October 1986, Q_{90}, and Q_{50} levels.

One consideration of the ability of the flow system to withstand development of ground-water resources in the Upper Floridan aquifer by pumpage is the gain in streamflow over the basin for October 1986, Q_{90}, and Q_{50} conditions. Streamflow gain is the net accumulation of flow by all streams in the study area, and is

computed as the difference between streamflow exiting and entering the study area. Positive values indicate that sources of water to the flow system, such as lateral-boundary flow, vertical leakage to aquifers, or channel precipitation, exceed the demand, allowing the "excess" to discharge to streams. Negative values indicate a loss of water, perhaps caused by overpumping during drought conditions. This is not to say that all streamflow gain is available for development through pumpage of ground water. If all streamflow gain is utilized by pumpage, then streams that rise in the study area would be dry; hence, total development of these resources are impractical. Other streams, such as the Chattahoochee and Flint River, depend on streamflow gain to maintain flow at an acceptable rate for economic, environmental, health, navigational, and recreational purposes. The amount of streamflow gain that can be developed by intercepting the ground-water component through pumpage, or by direct, off-channel withdrawal, varies with total flow and is the object of concern to water-resource managers.

Streamflow gain can be compared with hypothetical or real pumping rates to determine the development potential of ground-water resources. Values for streamflow entering the study area for October 1986, Q_{90}, and Q_{50} conditions were obtained from data at measurement sites that were located at or near the study area boundary (pl. 1). Streamflow leaving the study area is given by flow in the Apalachicola River near Sumatra, Fla. These values and the streamflow gain are listed in table 37.

Another generalization about development potential of ground-water resources in the Upper Floridan aquifer can be made by analyzing pumping rates that would produce a given percent of streamflow reduction under steady-state conditions. Simulated pumping rates that cause 1-to-4-percent reductions in the total flow of the Apalachicola River near Sumatra, Fla., were compiled from figure 50 and listed in table 38. These rates indicate that for a given percent-streamflow reduction, about half as much water can be pumped from the Upper Floridan aquifer when flow at Sumatra, Fla., is at the Q_{90} level than when flow is at the Q_{50} level. Similarly, about three-fourths as much water can be pumped for flow at the October 1986 level than at the Q_{90} level to achieve the same percent-streamflow reduction.

Potential development of ground water from the Upper Floridan aquifer can be evaluated in terms of pumping rates that yield a given percent-streamflow reduction for each of the 3 flows listed in table 38. The linear relation of percent-streamflow reduction to pumpage for each flow listed in table 38 allows a pumpage value to be computed for percentages of streamflow reduction other than those listed in table 38, but within the range of 1 to 4 percent. For example, to produce a 3.5-percent-streamflow reduction, values of the pumpage multiplier, *n*, applied to the October 1986 rates, are computed by linear interpolation of multipliers corresponding to streamflow reductions of 3 and 4 percent to yield *n* values of 0.58, 0.79, and 1.56, respectively, for the October 1986, Q_{90}, and Q_{50} flows.

Development potential of ground-water resources in the Upper Floridan aquifer can be evaluated in terms of the pumpage required to produce total-streamflow reductions of 1 to 4 percent for flows that range between October 1986 and Q_{50} levels. For a given total-streamflow reduction of the range 1 to 4 percent, pumpage varies consistently among the October 1986, Q_{90}, and Q_{50} flows in proportion to the relative fraction of streamflow that the smaller flow comprises of the larger. That is, Q_{90} flow (6,392 Mgal/d) is about half of Q_{50} flow (12,798 Mgal/d), and October 1986 flow (4,735 Mgal/d) is about three-fourths of Q_{90} flow. Therefore, pumpage required to produce given streamflow reductions of 1 to 4 percent for Q_{90} flow is half of that needed for Q_{50} flow, and pumpage required for October 1986 flow is about three-fourths of that needed for Q_{90} flow.

By interpolation within and between rows of table 38, the above linear relations can be used to compute pumping rates that would produce given streamflow reductions of 1 to 4 percent for any flow between October 1986 and Q_{50} levels. From the previous example, pumpage multipliers (*n*) for the October 1986 rates that would produce a 3.5-percent reduction in the Q_{90} and October 1986 flows can be computed from the *n* value obtained for Q_{50} flow as $0.5 \times 1.56 = 0.78$ for Q_{90} flow, and $0.75 \times 0.78 = 0.59$ for October 1986 flow; the slight discrepancy between this last value and that obtained previously (0.58) probably is due to slight nonlinearities in the flow system. Alternately, the pumpage multiplier for October 1986 flow can be computed di-

Table 37. Streamflow entering, leaving, and gain in the lower Apalachicola-Chattahoochee-Flint River Basin for October 1986, Q_{90}, and Q_{50} flow conditions

[Flow in million gallons per day; Q_{nn} is streamflow that is exceeded *nn* percent of the time

Streamflow	Streamflow condition		
	October 1986	Q_{90}	Q_{50}
Entering study area	2,497	2,021	8,022
Leaving study area1	4,735	6,392	12,798
Gain (leaving minus entering)	2,238	4,371	4,766

[1] Flow of Apalachicola River near Sumatra, Fla.; equals 4,735 Mgal/d for October 1986, 6,392 Mgal/d for Q_{90}, and 12,798 Mgal/d for Q_{50}. Accuracy of streamflow records is "good," except for those below 9,695 Mgal/d (15,000 cubic feet per second), which are tide affected and rated "fair." Good means that about 95 percent of the daily discharges are within 10 percent; and fair, within 15 percent.

rectly from the *n* value corresponding to Q_{50} flow as $0.75 \times 0.5 \times 1.56$, or 0.375×1.56, where 0.375 defines the fraction of the Q_{50} flow that is composed of the October 1986 flow. To continue with the example, for streamflow that is 60 percent of the Q_{50} flow ($0.6 \times 12{,}798$ Mgal/d$=7{,}679$ Mgal/d), the pumpage multiplier corresponding to a 3.5-percent-streamflow reduction is computed as $0.6 \times 1.56 = 0.94$.

Development potential of the Upper Floridan aquifer can be evaluated with regard to pumpage effects on total streamflow by the manner described in the above discussion and examples. Linear relations among total streamflow, percent-streamflow reduction, and pumpage limit the evaluation to pumpage up to and including twice the October 1986 rates and flows that range from October 1986 to Q_{50} levels. Maximum streamflow reductions that obey the linear relations described above increase with decreased total streamflow, and are defined as the percent values corresponding to pumpage-multiplier $n=2$ (table 36; fig. 50). These values are 4.5, 9.2 and 12.5 percent for Q_{50}, Q_{90}, and October 1986 flows, respectively. Different, perhaps nonlinear or piecewise-linear relations might exist that define larger maximum-percent-streamflow reductions than these values for pumpage between 2 and 5 times the October 1986 rates; however, additional simulations would be required to develop these relations.

Further application of the linear relations described above can be made to obtain values of minimum streamflow needed to satisfy criteria related to maximum-allowable-streamflow reductions for a given pumping rate. However, establishment of such criteria requires interpretation of the analyses presented here with regard to political, economic, and resource-management objectives and is beyond the scope of this report.

CONCLUSIONS

Changes in surface- and ground-water levels in Georgia have mixed effects on the ground-water resources of Alabama. Simulations made using a flow model of the Upper Floridan aquifer indicate that pumpage-induced changes to ground-water levels in the Upper Floridan aquifer in Georgia have little or no affect on ground-water levels and, hence, on development potential in Alabama. For simulation of the largest increase to October 1986 pumpage (multiple of 5), ground-water-level declines of less than 5 ft were simulated across the Chattahoochee River in Alabama, less than 10 mi from areas in Miller County, Ga., where aquifer dewatering and more than 80 ft of water-level decline were simulated. For simulated pumpage of less than 5 times the October 1986 rate, ground-water-level change in Georgia did not extend beyond the Chattahoochee River. The small water-level declines that occurred in Alabama as a result of larger declines in Georgia have a minimal affect on the water-transmitting capacity of the Upper Floridan aquifer; thus, the potential for ground-water development in Alabama is not compromised by pumpage in Georgia.

There are at least two reasons for the apparent attenuation of pumpage effects in Georgia at the Chattahoochee River. One is that the natural direction of ground-water flow to the river is not disrupted by pumpage in Georgia, even in areas exhibiting large ground-water-level declines. The ability of water levels in the

Table 38. Simulated pumping rates that cause 1-to-4-percent reductions in flow of Apalachicola River near Sumatra, Fla., for flows at October 1986, Q_{90}, and Q_{50} levels

[Mgal/d, million gallons per day; $Q_{OCT\ 86}$, flow at October 1986 level]

Percent streamflow reduction	Pumpage (*n*) x October 1986 rates by streamflow[1]					
	n	$Q_{OCT\ 86}$ (Mgal/d)	n	Q_{90} (Mgal/d)	n	Q_{50} (Mgal/d)
1	0.17	81	0.23	109	0.45	214
2	.34	162	.46	219	.9	428
3	.5	237	.68	325	1.34	637
4	.66	314	.89	423	1.78	847

[1] Flow of Apalachicola River near Sumatra, Fla.; equals 4,735 Mgal/d for October 1986, 6,392 Mgal/d for Q_{90}, and 12,798 Mgal/d for Q_{50}. Accuracy of streamflow records is "good," except for those below 9,695 Mgal/d (15,000 cubic feet per second), which are tide affected and rated "fair." Good means that about 95 percent of the daily discharges are within 10 percent; and fair, within 15 percent.

Upper Floridan aquifer in Miller County to withstand over 80 ft of decline and still provide a positive hydraulic gradient to the Chattahoochee River is indicated by the combination of sharp-upstream bending of potentiometric contours at the river and a symmetric pattern to the dissipation of water-level declines that originate in central Miller County; a pattern that is only slightly affected by the river. The second reason for the cessation of pumpage effects in Georgia at the Chattahoochee River is the sparse distribution of pumped wells in Alabama and Florida, or, specifically, the paucity data to support pumpage in these two states. Simulations are based on pumpage data for October 1986, which indicates that pumpage in Georgia constitutes about 98 percent of total pumpage in the study area. Therefore, simulation of changes in magnitude of pumping rates can be viewed as a sensitivity analysis of the flow system to increased pumpage in Georgia.

Changes in stream stage have negligible effects on the development potential of ground-water resources in the Upper Floridan aquifer in Alabama. Simulation of stream stage at Q_{90} levels and pumpage at half the October 1986 rates indicates increases in ground-water levels from October 1986 conditions of less than 0.5 ft in Alabama. For stream stage at higher, Q_{50} levels, simulated ground-water levels increased by about 1 ft over October 1986 levels in areas of Alabama located within a few miles of the Chattahoochee River, with most water-level increases being less than 0.5 ft. Thus, no appreciable gain in ground-water resources or development potential over October 1986 conditions is achieved from increased stream stage.

Ground-water resources in Alabama are affected more by changes in lateral and vertical boundary conditions than by surface-water levels or pumpage in Georgia. Changes in these boundaries from October 1986 conditions to those representing long-term-average, or "normal" conditions produced simulated ground-water-level increases that range from 1 to 15 ft. The effect of these increases on development potential is critical, as the largest water-level increases occurred in areas where the Upper Floridan aquifer is less than 100-ft thick. Thus, the water-transmitting capacity of the aquifer and availability of ground-water resources is increased by 15 to 30 percent by virtue of water-level increases that occur naturally each year from annual recharge. However, this apparent increase in resource capacity and development potential diminishes with seasonal water-level declines, despite the absence of pumpage, as simulations have indicated.

Locations that can be classified as containing high or low development potential for ground-water resources are masked in some areas by incomplete hydrologic information that precludes anything but general statements to be made about simulated response to pumpage in large geographic areas. Issues that are pertinent to classifying development potential as either high or low center around sustainability of the resource once pumpage is instituted, and address the following hydrological, geotechnical, and engineering concerns:

- Aquifer dewatering
- Water-level declines that cause existing wells or pump depths to be too shallow for deep production zones
- Sinkhole development

- Reduction, depletion, or reversal of stream-aquifer flow

The degree to which any of these concerns are experienced or addressed in specific areas of the basin determines the potential for development of ground-water resources in the Upper Floridan aquifer. For example, some aquifer dewatering might be acceptable and occurs regularly during the growing season at the present time. Whether deeper wells should be drilled to tap more of the resource or existing pumps set deeper is a question that only can be answered on a site-specific basis after collecting and evaluating appropriate hydrologic information and weighing nonhydrologic issues such as economy, social awareness, water-use practices, and resource conservation. Comparison of maps showing ground-water-level change and aquifer thickness can be used to identify areas where aquifer dewatering is possible if the simulated, hypothetical pumpage scenarios come true and if aquifer-thickness data are available to verify model results. Sinkholes and other collapse features of the aquifer matrix have been known to form in the absence of pumpage so that regulation of pumpage still might not mitigate their occurrence. Although changes to natural discharge and recharge of streams by ground water is influenced directly by pumpage, stream-aquifer flows have indicated that measured and simulated effects are not equally distributed among all streams in the basin. Bias in the spatial distribution of ground-water-level and streamflow-measurement locations limits the ability of the data to detect flow-system response to pumpage and hampers an equitable assessment of development potential in areas that might be suitable for future resource development.

Current and potential, future ground-water withdrawals in southwestern Georgia and southeastern Alabama can cause notable measurable effects on stream-aquifer flow that reduce flow to the Apalachicola River and Bay, particularly during low-flow periods such as droughts. Pumpage-induced stream-aquifer-flow declines, that is, reduction in ground-water discharge to streams, was simulated for all pumpage scenarios in the 37 stream reaches located throughout the study area for which streamflow data permitted such an analysis. Although pumpage at 5 times the October 1986 rate occurs normally during the height of the growing season, surface- and ground-water levels that control lateral and vertical boundary conditions to the Upper Floridan aquifer and Intermediate system are higher during the growing season than in October 1986. Increased water levels at flow boundaries cause an increase in available ground water during the growing season, in contrast to the low-water-level conditions that exist at the end of the growing season, such as in October. Thus, increased pumpage at the end of the growing season and during a drought year, such as 1986, exacerbates the negative effects of pumpage on ground- and surface-water resources.

Reductions in stream-aquifer flow of about 1,300 to 1,400 million gallons per day were simulated with the Upper Floridan model for steady-state scenarios using 5 times the October 1986 pumpage and dry (October 1986) and normal boundary conditions. Although these reductions represent about 50 percent of the total stream-aquifer flow that would occur under dry conditions with no pumpage, and about 42 percent of what would occur under normal conditions, it is unlikely that actual pumpage would cause reductions in stream-aquifer flow of this magnitude. Usually, high-pumpage, low-streamflow events, which were simulated to steady-state, or equilibrium with regard to stream-aquifer flow, do not persist for more than about 1 or 2 months. During this time, transient effects in the flow system would permit about 33 to 80 percent of the steady-state, stream-aquifer-flow reduction to occur, which is about 430 to 1,100 million gallons per day. These rates translate to reductions in total streamflow of about 8 to 23 percent for October 1986 conditions, and about 6 to 17 and 3 to 6 percent, respectively, for streamflow at Q_{90} and Q_{50} levels. Because simulated pumpage in Alabama and Florida was small, these reductions in streamflow can be interpreted as caused solely by pumpage in Georgia.

Water budgets that describe the volume of water entering and exiting the subarea, and include processes such as recharge by precipitation and ground- and surface-water inflow and outflow, indicate the relative importance of each hydrologic component to ground-water resources of the Upper Floridan aquifer and Intermediate system. Budgets prepared from results of 36 simulations of the Upper Floridan and Intermediate models indicate that discharge to streams and recharge by horizontal and vertical flow are the principal hydrologic mechanisms for moving water into, out of, and through the aquifers. Recharge by precipitation is manifested in the water level of the overlying surficial deposits and aquifer itself, thus, rates of vertical leakage and lateral-boundary (regional) flow are the result of recharge by precipitation on the flow system.

Recharge to the Upper Floridan aquifer by regional inflow across lateral boundaries and by flow from outcrop areas varies considerably by state and is affected by simulated pumpage. For conditions of simulated pumpage, about 60 to 70 percent of recharge by these hydrologic mechanisms enters the Upper Floridan aquifer in Florida, about 25 to 35 percent enters in Georgia, and less than 5 percent enters in Alabama. Under zero-pumpage conditions, recharge to the Upper Floridan aquifer from outcrop areas in Alabama and Georgia constitutes only about 2 to 3 percent of total inflow to the aquifer.

Although simulated pumpage induces about 5 percent more flow from outcrop areas than exists under zero-pumpage conditions, conditions of dry or normal water levels along lateral- and vertical-flow boundaries noticeably affect the distribution of inflow from outcrop areas. Dry conditions tend to increase flow from outcrop areas in Georgia while decreasing similar flows from Alabama, in comparison with inflows simulated for normal conditions. Simulated pumpage with normal conditions of water levels along lateral and vertical boundaries resulted in slightly more than one-third of the total inflow to the Upper Floridan aquifer originating from outcrop areas in Alabama, which is disproportionately more flow from Alabama than Georgia compared with the relative size of outcrop areas in each state. However, the main contributor of recharge, at about 70 percent of the total, is vertical leakage from the undifferentiated overburden. This is expected, considering the small outcrop area of the Upper Floridan aquifer compared with its areal extent and subsequent coverage with overburden. What is not expected, however, is the relatively large percentage (about 30 percent for zero-pumpage scenarios) of recharge, excluding flow from outcrop areas, that originates from outside the basin and enters as regional flow.

Changes to water-budget components caused by simulated pumpage indicate that about 80 to 85 percent of the water pumped from the Upper Floridan aquifer is derived from regional flow and vertical leakage from the overburden. Actual percentages for these sources of pumped water could be less than simulated because aquifer water levels located outside the model area, that control regional flow, and in source layers, that control vertical leakage, were assumed to be unaffected by pumpage in the Upper Floridan aquifer. Additional water-level data would be needed to substantiate the validity of these assumptions. Regardless, simulation results indicate that the origin of ground water in the Upper Floridan aquifer and hydrologic processes controlling its movement are important considerations when attempting to resolve or mitigate isssues related to resource development in the study area.

Water budgets for the Intermediate system indicate that the flow system transmits and receives most of its water as vertical leakage to and from overlying surficial deposits and the underlying Upper Floridan aquifer, and ultimately discharges ground water to streams. Because pumpage in the Intermediate system and pumpage effects from the Upper Floridan aquifer in Georgia are negligible, the flow system consists almost entirely of these flow-through-leakage features and discharge to streams. About 25 to 30 percent of the total recharge enters the water-bearing units as regional flow, which originates entirely in Florida. Compared with water-budget components of the Upper Floridan aquifer, the contribution to streamflow by the Intermediate system is less than 2 percent of total stream-aquifer flow under dry, zero-pumpage conditions. Thus, the Intermediate system plays a minor, if not negligible, role in the hydrodynamics of the basin for providing flow to the Apalachicola River and Bay.

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Tables 14–31 and figures 25–42 and 44–48 follow.

Table 14. Net changes in water-budget components for simulations of increased pumpage with dry conditions of boundary and semiconfining-unit head and stream stage at October 1986 levels, corresponding to scenarios R1Pn (*n*=0.5, 1, 2, 5) of simulation matrix (table 1)

[Net changes computed from rates given by appropriate zero-pumpage simulation listed in table 10]

Budget component	Pumpage (*n* x October 1986 rates)			
	0.5	1	2	5
	Volumetric rates (million gallons per day)			
Well discharge	237	475	949	2,375
<u>Reduced discharge to</u>:				
Streams and in-channel springs[1]	144	289.8	590.1	1,276
Off-channel springs[2]	0	0	0	0
Regional flow	13.8	27.1	52.4	117.5
Undifferentiated overburden	7.9	15.5	28	43.7
<u>Induced recharge from</u>:				
Undifferentiated overburden	57.8	113.7	213.3	491.6
Regional flow	9.1	18.9	40.2	122.4
Upper Floridan aquifer outcrop	4.3	8.8	17.8	45
Streams	0.2	0.7	6.4	237.6

Budget component	Well discharge (percent)			
Well discharge	100	100	100	100
<u>Reduced discharge to</u>:				
Streams and in-channel springs[1]	60.7	61.1	62.3	54.7
Off-channel springs[2]	0	0	0	0
Regional flow	5.8	5.7	5.5	5
Undifferentiated overburden	3.4	3.3	3	1.9
<u>Induced recharge from</u>:				
Undifferentiated overburden	24.4	24	22.5	21.1
Regional flow	3.9	4	4.2	5.3
Upper Floridan aquifer outcrop	1.8	1.9	1.9	1.9
Streams	0.1	0.1	0.7	10.2

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

Table 15. Net changes in water-budget components for simulations of increased pumpage with normal conditions of boundary and semiconfining-unit head and stream stage at October 1986 levels, corresponding to scenarios R2P*n* (*n*=0.5, 1, 2, 5) of simulation matrix (table 1)

[Net changes computed from rates given by appropriate zero-pumpage simulation listed in table 11]

Budget component	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
	Volumetric rates (million gallons per day)			
Well discharge	237	475	949	2,375
Reduced discharge to:				
Streams and in-channel springs[1]	142.4	286.1	581.8	1,406
Off-channel springs[2]	0	0	0	0
Regional flow	10.8	21.1	40.9	91.6
Undifferentiated overburden	6.1	10.3	16.2	25.1
Induced recharge from:				
Undifferentiated overburden	61.7	123.7	240.6	540.8
Regional flow	12	24.5	50.8	143.9
Upper Floridan aquifer outcrop	4.2	8.5	17.2	43.5
Streams	0.1	0.3	1.7	102.7
Budget component	**Well discharge (percent)**			
Well discharge	100	100	100	100
Reduced discharge to:				
Streams and in-channel springs[1]	60	60.3	61.3	59.7
Off-channel springs[2]	0	0	0	0
Regional flow	4.6	4.5	4.3	3.9
Undifferentiated overburden	2.6	2.2	1.7	1.1
Induced recharge from:				
Undifferentiated overburden	26	26.1	25.4	23
Regional flow	5.1	5.2	5.4	6.1
Upper Floridan aquifer outcrop	1.8	1.8	1.8	1.9
Streams	0.1	0.1	0.2	4.4

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

Table 16. Net changes in water-budget components for simulations of increased pumpage with dry conditions of boundary and semiconfining-unit head and stream stage at Q_{90} levels, corresponding to scenarios R3P*n* (*n*=0.5, 1, 2, 5) of simulation matrix (table 1)

[Net changes computed from rates given by appropriate zero-pumpage simulation listed in table 10; Q_{90} is flow that is exceeded 90 percent of the time]

Budget component	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
	Volumetric rates (million gallons per day)			
Well discharge	237	475	949	2,375
Reduced discharge to:				
Streams and in-channel springs[1]	143.7	288.9	587.6	1,268
Off-channel springs[2]	0	0	0	0
Regional flow	13.9	27.3	52.7	118.5
Undifferentiated overburden	8.4	16.1	29.6	46.4
Induced recharge from:				
Undifferentiated overburden	57.6	113.8	213.3	493.3
Regional flow	9.1	18.8	40	121.6
Upper Floridan aquifer outcrop	4.4	8.8	17.8	43.4
Streams	0.2	0.9	8.2	243.1
Budget component	**Well discharge (percent)**			
Well discharge	100	100	100	100
Reduced discharge to:				
Streams and in-channel springs[1]	60.6	60.9	61.9	54.3
Off-channel springs[2]	0	0	0	0
Regional flow	5.9	5.8	5.6	5.1
Undifferentiated overburden	3.5	3.4	3.1	2
Induced recharge from:				
Undifferentiated overburden	24.3	24	22.5	21.1
Regional flow	3.9	4	4.2	5.2
Upper Floridan aquifer outcrop	1.8	1.9	1.9	1.9
Streams	0.1	0.2	0.9	10.4

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

Table 17. Net changes in water-budget components for simulations of increased pumpage with normal conditions of boundary and semiconfining-unit head and stream stage at Q_{90} levels, corresponding to scenarios R4P*n* (*n*=0.5, 1, 2, 5) of simulation matrix (table 1)

[Net changes computed from rates given by appropriate zero-pumpage simulation listed in table 11; Q_{90} is flow that is exceeded 90 percent of the time]

	Pumpage (*n* x October 1986 rates)			
	0.5	**1**	**2**	**5**
Budget component	**Volumetric rates (million gallons per day)**			
Well discharge	237	475	949	2,375
Reduced discharge to:				
Streams and in-channel springs[1]	142.2	285.7	579.9	1,401
Off-channel springs[2]	0	0	0	0
Regional flow	10.9	21.3	41.2	92.5
Undifferentiated overburden	6.7	11.6	17.9	27.3
Induced recharge from:				
Undifferentiated overburden	61.2	122.9	240.1	542.9
Regional flow	11.9	24.3	50.4	143.1
Upper Floridan aquifer outcrop	4.2	8.5	17.2	43.8
Streams	0.1	0.3	2.3	4.4
Budget component	**Well discharge (percent)**			
Well discharge	100	100	100	100
Reduced discharge to:				
Streams and in-channel springs[1]	59.9	60.2	61.1	59.4
Off-channel springs[2]	0	0	0	0
Regional flow	4.6	4.5	4.3	3.9
Undifferentiated overburden	2.8	2.4	1.9	1.2
Induced recharge from:				
Undifferentiated overburden	25.8	25.9	25.3	23
Regional flow	5	5.1	5.3	6.1
Upper Floridan aquifer outcrop	1.8	1.8	1.8	1.9
Streams	0.1	0.1	0.2	4.6

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

Table 18. Net changes in water-budget components for simulations of increased pumpage with dry conditions of boundary and semiconfining-unit head and stream stage at Q_{50} levels, corresponding to scenarios R5P*n* (*n*=0.5, 1, 2, 5) of simulation matrix (table 1)

[Net changes computed from rates given by appropriate zero-pumpage simulation listed in table 10; Q_{50} is flow that is exceeded 50 percent of the time]

Budget component	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
	Volumetric rates (million gallons per day)			
Well discharge	237	475	949	2,375
Reduced discharge to:				
Streams and in-channel springs[1]	142.2	285.4	577.4	1,226
Off-channel springs[2]	0	0	0	0
Regional flow	14.3	28.1	54.3	124.9
Undifferentiated overburden	8.9	17.6	34	59.5
Induced recharge from:				
Undifferentiated overburden	57.8	113.8	212.8	488.3
Regional flow	8.7	17.9	38.4	115.5
Upper Floridan aquifer outcrop	4.4	8.8	17.8	45.3
Streams	0.9	2.9	14.2	277.6

Budget component	Well discharge (percent)			
Well discharge	100	100	100	100
Reduced discharge to:				
Streams and in-channel springs[1]	60	60.1	60.8	52.5
Off-channel springs[2]	0	0	0	0
Regional flow	6	5.9	5.7	5.3
Undifferentiated overburden	3.4	3.7	3.6	2.5
Induced recharge from:				
Undifferentiated overburden	24.4	24	22.4	20.9
Regional flow	3.7	3.8	4.1	4.9
Upper Floridan aquifer outcrop	1.9	1.9	1.9	1.9
Streams	0.4	0.6	1.5	11.9

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

Table 19. Net changes in water-budget components for simulations of increased pumpage with normal conditions of boundary and semiconfining-unit head and stream stage at Q_{50} levels, corresponding to scenarios R6P*n* (*n*=0.5, 1, 2, 5) of simulation matrix (table 1)

[Net changes computed from rates given by appropriate zero-pumpage simulation listed in table 11; Q_{50} is flow that is exceeded 50 percent of the time]

Budget component	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
	Volumetric rates (million gallons per day)			
Well discharge	237	475	949	2,375
Reduced discharge to:				
Streams and in-channel springs[1]	141.7	284.4	576	1,378
Off-channel springs[2]	0	0	0	0
Regional flow	11.1	21.8	42.4	96.4
Undifferentiated overburden	7.9	15.3	26.5	38.9
Induced recharge from:				
Undifferentiated overburden	60.6	120.4	234.4	538
Regional flow	11.7	23.8	49.2	139.5
Upper Floridan aquifer outcrop	4.2	8.5	17.2	43.9
Streams	0.1	0.4	3.5	123.6

Budget component	Well discharge (percent)			
Well discharge	100	100	100	100
Reduced discharge to:				
Streams and in-channel springs[1]	59.7	59.9	60.7	58.4
Off-channel springs[2]	0	0	0	0
Regional flow	4.7	4.6	4.5	4.1
Undifferentiated overburden	3.3	3.2	2.8	1.7
Induced recharge from:				
Undifferentiated overburden	25.5	25.4	24.7	22.8
Regional flow	4.9	5	5.2	5.9
Upper Floridan aquifer outcrop	1.8	1.8	1.8	1.9
Streams	0.1	0.1	0.4	5.2

[1] In-channel springs discharge in or near streams and contribute to streamflow.

[2] Off-channel springs are located away from streams and do not contribute to streamflow.

Table 20. Computed net stream-aquifer flow from pumping scenarios R1P*n* (*n*=0.5, 1, 2, 5) simulating dry conditions of boundary and semiconfining-unit head and stream stage at October 1986 levels (table 1)

[Negative values indicate recharge to aquifer by streamflow]

Reach (pl. 9)	Stream	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
		Computed net stream-aquifer flow (million gallon per day)			
1	Gum Creek	2.9	2.3	1.1	0
2	Cedar Creek	.9	.8	.6	.1
3	Swift Creek	2.6	2.5	2.2	1.4
4	Jones Creek	1.7	1.5	1	0
5	Abrams Creek	1.9	1.7	1.2	.1
6	Mill Creek	4.7	4.5	3.8	2
7	Cooleewahee Creek	.5	.3	.1	0
8	Chickasawhatchee Creek	2.6	2.6	2.6	2.5
9	Chickasawhatchee Creek	.3	.2	.2	.2
10	Chickasawhatchee Creek	2	1.8	1.5	.5
11	Dry Creek (Ga.)	2	1.8	1.4	.3
12	Spring Creek	2.5	2.3	1.7	.3
13	Spring Creek	16.1	12.6	5.9	.5
14	Spring Creek	2.6	.7	0	0
15	Sawhatchee Creek	6.3	6.2	5.9	5.1
16	Cowarts Creek	12.9	12.9	12.7	12.2
17	Marshall Creek	20.5	20.4	20.3	20
18	Spring Creek	34.2	27.3	9.9	0
19	Dry Creek (Fla.)	27.3	27.2	27.1	26.7
20	Ichawaynochaway Creek	34.7	34	32.5	27.6
21	Ichawaynochaway Creek	15.8	15.3	14.3	10.7
22	Muckalee Creek	15.	11.5	4.5	−11.3
23	Muckalee Creek	3.7	2.5	0.1	−5.2
24	Muckalee Creek	9.7	9.2	8.1	5.6
25	Kinchafoonee Creek	−1.5	−1.5	−1.5	−1.5
26	Kinchafoonee Creek	4.3	3.8	2.8	0.6
27	Chipola River	74.4	74.1	73.4	71.2
28	Chipola River	219.6	219.4	218.9	217.4
29	Chipola River	232.1	232	231.9	231.6
30	Flint River	4.7	4.1	2.8	0.1
31	Flint River	407	390.8	358.4	260.4
32	Flint River	364.8	347.1	311.6	203.5
33	Flint River	256.2	234.8	190.6	48.2
34	Flint River	254.8	227.5	167.6	−49.2
35	Apalachicola River	182.3	181.9	181.1	178.3
36	Apalachicola River	107	106.9	106.6	105.7
37	Apalachicola River	337.7	337.7	337.7	337.7

Table 21. Computed net stream-aquifer flow from pumping scenarios R1P*n* (*n*=0.5, 1, 2, 5) simulating dry conditions of boundary and semiconfining-unit head and stream stage at October 1986 levels (table 1)

[Negative values indicate recharge to aquifer by streamflow]

Reach (pl. 9)	Stream	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
		Computed net stream-aquifer flow (million gallon per day)			
1	Gum Creek	3.9	3.3	2.1	0
2	Cedar Creek	1.2	1.1	.9	.4
3	Swift Creek	3.4	3.2	3	2.1
4	Jones Creek	2.2	1.9	1.4	.1
5	Abrams Creek	2.4	2.2	1.7	.5
6	Mill Creek	6.1	5.7	5	3.2
7	Cooleewahee Creek	3	2.6	2	.7
8	Chickasawhatchee Creek	3.7	3.7	3.7	3.6
9	Chickasawhatchee Creek	2.6	2.6	2.4	1.9
10	Chickasawhatchee Creek	6.8	6.5	5.9	3.8
11	Dry Creek (Ga.)	3	2.8	2.5	1.1
12	Spring Creek	3.9	3.7	3.1	1.4
13	Spring Creek	23.5	20.2	13.2	1.4
14	Spring Creek	4.4	2	.1	0
15	Sawhatchee Creek	10.1	9.9	9.8	8.9
16	Cowarts Creek	17.3	17.2	17.1	16.7
17	Marshall Creek	29.8	29.8	29.7	29.3
18	Spring Creek	38.7	32	16.5	0
19	Dry Creek (Fla.)	47.9	47.8	47.7	47.2
20	Ichawaynochaway Creek	51	50.3	48.9	44.4
21	Ichawaynochaway Creek	23.1	22.6	21.7	18.5
22	Muckalee Creek	19.2	15.7	8.7	−8.1
23	Muckalee Creek	4.7	3.6	1.2	−4.3
24	Muckalee Creek	11.6	11.2	10.3	7.8
25	Kinchafoonee Creek	−1.5	−1.5	−.5	−1.5
26	Kinchafoonee Creek	4.7	4.3	3.4	.8
27	Chipola River	110.7	110.4	109.8	107.8
28	Chipola River	250.3	250.1	249.7	248.3
29	Chipola River	251.2	251.2	251.1	250.8
30	Flint River	5.4	4.8	3.6	.6
31	Flint River	457.5	441.5	409.5	313.1
32	Flint River	416.3	398.6	363.2	256.4
33	Flint River	324.3	303.4	260.5	123.2
34	Flint River	292.6	266.2	209.3	−1.6
35	Apalachicola River	216.3	216	215.2	212.5
36	Apalachicola River	135.7	135.6	135.3	134.4
37	Apalachicola River	345.2	345.2	345.2	345.2

Table 22. Computed net stream-aquifer flow from pumping scenarios R3P*n* (*n*=0.5, 1, 2, 5) simulating dry conditions of boundary and semiconfining-unit head and stream stage at Q_{90} levels (table 1)

[Negative values indicate recharge to aquifer by streamflow]

Reach (pl. 9)	Stream	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
		Computed net stream-aquifer flow (million gallon per day)			
1	Gum Creek	3.4	2.7	1.4	0
2	Cedar Creek	.9	.8	.6	.1
3	Swift Creek	2.6	2.5	2.1	1.3
4	Jones Creek	1.8	1.6	1	0
5	Abrams Creek	1.9	1.7	1.2	.1
6	Mill Creek	4.7	4.4	3.8	1.9
7	Cooleewahee Creek	.4	.3	.1	0
8	Chickasawhatchee Creek	2.6	2.6	2.5	2.5
9	Chickasawhatchee Creek	.2	.2	.2	.1
10	Chickasawhatchee Creek	1.9	1.7	1.4	.5
11	Dry Creek (Ga.)	1.9	1.7	1.4	.3
12	Spring Creek	2.5	2.2	1.6	.3
13	Spring Creek	15.4	12	5.4	.4
14	Spring Creek	2.3	.5	0	0
15	Sawhatchee Creek	6.3	6.2	5.9	5.1
16	Cowarts Creek	12.8	12.7	12.5	12.1
17	Marshall Creek	20.3	20.2	20.1	19.8
18	Spring Creek	33.3	26.3	9.1	0
19	Dry Creek (Fla.)	26.9	26.9	26.7	26.3
20	Ichawaynochaway Creek	33.8	33.1	31.6	26.7
21	Ichawaynochaway Creek	15.6	15.1	14	10.5
22	Muckalee Creek	12.9	9.4	2.5	−14.1
23	Muckalee Creek	3.2	2	−0.4	−5.9
24	Muckalee Creek	7.2	6.7	5.7	3.2
25	Kinchafoonee Creek	−1.5	−1.5	−1.5	−1.5
26	Kinchafoonee Creek	4.5	4	3	.5
27	Chipola River	73.5	73.2	72.5	70.3
28	Chipola River	233.7	233.4	232.9	231.4
29	Chipola River	294.6	294.5	294.4	294.1
30	Flint River	4.8	4.2	2.9	.1
31	Flint River	407.3	391.2	358.8	260.8
32	Flint River	361.2	343.6	308.1	200.2
33	Flint River	253	231.7	187.5	45.2
34	Flint River	254.1	226.8	167	−49.9
35	Apalachicola River	173.4	173	172.2	169.4
36	Apalachicola River	95.9	95.7	95.5	94.6
37	Apalachicola River	310.6	310.6	310.6	310.6

Table 23. Computed net stream-aquifer flow from pumping scenarios R4P*n* (*n*=0.5, 1, 2, 5) simulating normal conditions of boundary and semiconfining-unit head and stream stage at Q_{90} levels (table 1)

[Negative values indicate recharge to aquifer by streamflow; Q_{90} is flow that is exceeded 90 percent of the time]

Reach (pl. 9)	Stream	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
		Computed net stream-aquifer flow (million gallon per day)			
1	Gum Creek	4.5	3.7	2.4	0
2	Cedar Creek	1.2	1.1	.9	.4
3	Swift Creek	3.4	3.2	2.9	2.1
4	Jones Creek	2.3	1.9	1.4	.2
5	Abrams Creek	2.4	2.2	1.7	.5
6	Mill Creek	6.1	5.7	5	3.1
7	Cooleewahee Creek	2.7	2.4	1.8	.6
8	Chickasawhatchee Creek	3.6	3.6	3.6	3.5
9	Chickasawhatchee Creek	2.5	2.5	2.3	1.7
10	Chickasawhatchee Creek	6.7	6.3	5.7	3.7
11	Dry Creek (Ga.)	2.9	2.7	2.4	1
12	Spring Creek	3.8	3.6	3	1.2
13	Spring Creek	22.9	19.6	12.7	1.2
14	Spring Creek	4.1	1.7	0	0
15	Sawhatchee Creek	10.1	9.9	9.7	8.9
16	Cowarts Creek	17.2	17.1	17	16.5
17	Marshall Creek	29.7	29.6	29.5	29.1
18	Spring Creek	37.7	31	15.6	0
19	Dry Creek (Fla.)	47.4	47.4	47.2	46.8
20	Ichawaynochaway Creek	50	49.4	47.9	43.5
21	Ichawaynochaway Creek	22.9	22.4	21.4	18.3
22	Muckalee Creek	16.9	13.6	6.6	–11.4
23	Muckalee Creek	4.1	3	0.6	-5.2
24	Muckalee Creek	9.1	8.7	7.8	5.2
25	Kinchafoonee Creek	–1.5	–1.5	–1.5	–1.5
26	Kinchafoonee Creek	4.8	4.4	3.5	.5
27	Chipola River	109.8	109.5	108.9	106.9
28	Chipola River	264.3	264.1	263.7	262.3
29	Chipola River	313.7	313.7	313.6	313.2
30	Flint River	5.5	4.9	3.6	.6
31	Flint River	457.7	441.7	409.8	313.4
32	Flint River	412.7	395	359.6	252.9
33	Flint River	321.1	300.2	257.4	120
34	Flint River	291.8	265.5	208.7	–2.5
35	Apalachicola River	207.5	207.1	206.3	203.6
36	Apalachicola River	127.4	127.3	126.9	126
37	Apalachicola River	310.7	310.7	310.7	310.7

Table 24. Computed net stream-aquifer flow from pumping scenarios R5P*n* (*n*=0.5, 1, 2, 5) simulating dry conditions of boundary and semiconfining-unit head and stream stage at Q_{50} levels (table 1)

[Negative values indicate recharge to aquifer by streamflow; Q_{50} is flow that is exceeded 50 percent of the time]

Reach (pl. 9)	Stream	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
		Computed net stream-aquifer flow (million gallon per day)			
1	Gum Creek	2.8	2.2	1.0	0
2	Cedar Creek	.7	.6	.5	.1
3	Swift Creek	2.2	2.1	1.8	1
4	Jones Creek	1.7	1.4	.9	0
5	Abrams Creek	1.8	1.6	1	.1
6	Mill Creek	4.5	4.1	3.6	1.7
7	Cooleewahee Creek	.1	0	0	0
8	Chickasawhatchee Creek	2.3	2.3	2.3	2.2
9	Chickasawhatchee Creek	.1	.1	.1	.1
10	Chickasawhatchee Creek	1.8	1.6	1.3	.4
11	Dry Creek (Ga.)	2	1.8	1.5	.3
12	Spring Creek	2.6	2.3	1.7	.3
13	Spring Creek	16.3	12.9	6.1	.5
14	Spring Creek	3	.9	0	0
15	Sawhatchee Creek	5.9	5.7	5.5	4.7
16	Cowarts Creek	12.3	12.2	12	11.6
17	Marshall Creek	19.5	19.4	19.4	19
18	Spring Creek	35.4	28.6	11.6	0
19	Dry Creek (Fla.)	25.3	25.2	25.1	24.7
20	Ichawaynochaway Creek	32.4	31.7	30.2	25.4
21	Ichawaynochaway Creek	15.3	14.8	13.8	10.3
22	Muckalee Creek	12.3	8.8	1.8	−14.6
23	Muckalee Creek	3.0	1.8	−0.5	−5.9
24	Muckalee Creek	6.5	6.1	5.1	2.5
25	Kinchafoonee Creek	−1.5	−1.5	−1.5	−1.5
26	Kinchafoonee Creek	4.3	3.9	3	.4
27	Chipola River	69.8	69.5	68.9	66.7
28	Chipola River	290.1	289.9	289.4	287.9
29	Chipola River	438.4	438.3	438.2	437.9
30	Flint River	4.7	4.1	2.8	0.1
31	Flint River	398.4	382.2	349.9	252.3
32	Flint River	345.5	327.8	292.6	185.3
33	Flint River	243.2	221.9	177.9	36.3
34	Flint River	243.7	216.8	157.6	-58.0
35	Apalachicola River	165.8	165.4	164.7	161.8
36	Apalachicola River	75	74.9	74.5	73.6
37	Apalachicola River	59.9	59.9	59.9	59.9

Table 25. Computed net stream-aquifer flow from pumping scenarios R6P*n* (n = 0.5, 1, 2, 5) simulating normal conditions of boundary and semiconfining-unit head and stream stage at Q_{50} levels (table 1)

[Negative values indicate recharge to aquifer by streamflow; Q_{50} is flow that is exceeded 50 percent of the time]

Reach (pl. 9)	Stream	Pumpage (*n* ¥ October 1986 rates)			
		0.5	1	2	5
		Computed net stream-aquifer flow (million gallon per day)			
1	Gum Creek	3.9	3.2	1.9	0
2	Cedar Creek	1	1	.8	.3
3	Swift Creek	3	2.8	2.5	1.7
4	Jones Creek	2.1	1.9	1.3	.1
5	Abrams Creek	2.3	2.1	1.6	.3
6	Mill Creek	5.7	5.4	4.7	2.8
7	Cooleewahee Creek	2	1.7	1.3	.3
8	Chickasawhatchee Creek	3.4	3.4	3.3	3.2
9	Chickasawhatchee Creek	2.2	2.1	1.9	1.4
10	Chickasawhatchee Creek	6.3	6	5.4	3.4
11	Dry Creek (Ga.)	3	2.8	2.5	1.2
12	Spring Creek	3.9	3.7	3.2	1.4
13	Spring Creek	23.8	20.4	13.5	1.4
14	Spring Creek	4.8	2.3	.1	0
15	Sawhatchee Creek	9.6	9.5	9.3	8.5
16	Cowarts Creek	16.7	16.6	16.5	16
17	Marshall Creek	28.9	28.8	28.7	28.4
18	Spring Creek	39.9	33.1	18.1	0
19	Dry Creek (Fla.)	45.3	45.3	45.2	44.7
20	Ichawaynochaway Creek	48.6	47.9	46.5	42.1
21	Ichawaynochaway Creek	22.5	22.1	21.2	18
22	Muckalee Creek	16.3	12.9	5.9	−12.1
23	Muckalee Creek	3.9	2.8	.5	−5.4
24	Muckalee Creek	8.4	8	7.1	4.5
25	Kinchafoonee Creek	−1.5	−1.5	−1.5	−1.5
26	Kinchafoonee Creek	4.8	4.3	3.4	.4
27	Chipola River	106.1	105.8	105.2	103.2
28	Chipola River	320.7	320.5	320.1	318.7
29	Chipola River	457.5	457.4	457.4	457
30	Flint River	5.4	4.7	3.5	.4
31	Flint River	448.6	432.6	400.6	304.4
32	Flint River	396.5	378.9	343.6	237.2
33	Flint River	311.1	290.2	247.6	110.7
34	Flint River	281.1	255.1	198.9	-10.3
35	Apalachicola River	199.9	199.5	198.7	196
36	Apalachicola River	103.7	103.6	103.3	102.4
37	Apalachicola River	117.3	117.3	117.3	117.3

Table 26. Computed lateral-boundary (regional) flow rates by state from pumping scenarios R1P*n* (*n*=0.5, 1, 2, 5), Upper Floridan model, simulating dry conditions of boundary and semiconfining-unit head, and stream stage at October 1986 levels (table 1)

[Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Pumpage (*n* x October 1986 rates)			
		0.5	1	2	5
		Lateral-boundary flow (Mgal/d)			
	Alabama				
1	Upper Floridan aquifer outcrop	7.3	7.4	8.7	12.7
2	Basin divide, no flow	0	0	0	0
	Florida				
3	Southwestern boundary	434.4	434.8	435.6	438.3
4	Southern boundary	–20	–19.9	–19.6	–18.6
5	Southeastern boundary	184.3	185.3	187.3	195.2
	Georgia				
6	Southeastern boundary	–11.9	–11.3	–10	–5.2
7	Southern Solution Escarpment	–32.5	–20.1	4.8	82.2
8	Northern Solution Escarpment	–124.8	–119.5	–109.1	–77.6
9	Northeastern boundary	158.1	161.3	167.7	188.6
10	Northern boundary	0.1	0.2	0.6	1.8
11	Upper Floridan aquifer outcrop	116.9	121.2	128.9	152.2

Table 27. Computed lateral-boundary (regional) flow rates by state from pumping scenarios R1P*n* (*n*=0.5, 1, 2, 5), Upper Floridan model, simulating normal conditions of boundary and semiconfining-unit head, and stream stage at October 1986 levels (table 1)

[Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Pumpage (*n* x October 1986 rates) 0.5	1	2	5
		Lateral-boundary flow (Mgal/d)			
	Alabama				
1	Upper Floridan aquifer outcrop	33.5	33.8	35	38.7
2	Basin divide, no flow	0	0	0	0
	Florida				
3	Southwestern boundary	543.2	543.5	544.3	546.8
4	Southern boundary	33.5	33.7	34	34.8
5	Southeastern boundary	255.5	256.5	258.5	265.9
	Georgia				
6	Southeastern boundary	19.6	20.2	21.4	26
7	Southern Solution Escarpment	25	37.3	62.1	138.7
8	Northern Solution Escarpment	−133.8	−128.6	−118.3	−87.2
9	Northeastern boundary	160.7	163.8	170	189.8
10	Northern boundary	0.2	0.4	0.7	1.9
11	Upper Floridan aquifer outcrop	60	64	71.5	94.1

Table 28. Computed lateral-boundary (regional) flow rates by state from pumping scenarios R3P*n* (*n* = 0.5, 1, 2, 5), Upper Floridan model, simulating dry conditions of boundary and semiconfining-unit head and stream stage at Q_{90} levels (table 1)

[Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Pumpage (*n* x October 1986 rates)			
		0.5	1	2	5
		Lateral-boundary flow (Mgal/d)			
	Alabama				
1	Upper Floridan aquifer outcrop	9.5	9	9.7	12.1
2	Basin divide, no flow	0	0	0	0
	Florida				
3	Southwestern boundary	431.9	432.3	433.1	435.9
4	Southern boundary	–26.9	–26.8	–26.5	–25.5
5	Southeastern boundary	179.4	180.4	182.4	190.4
	Georgia				
6	Southeastern boundary	–12.2	–11.5	–10.3	–5.5
7	Southern Solution Escarpment	–34.1	–21.8	3.1	80.5
8	Northern Solution Escarpment	–125.8	–120.5	–110.1	–78.6
9	Northeastern boundary	157.9	161	167.5	188.5
10	Northern boundary	0	0.2	0.6	1.8
11	Upper Floridan aquifer outcrop	112.6	117.5	125.9	151.1

Table 29. Computed lateral-boundary (regional) flow rates by state from pumping scenarios R4P*n* (n = 0.5, 1, 2, 5), Upper Floridan model, simulating normal conditions of boundary and semiconfining-unit head and stream stage at Q_{90} levels (table 1)

[Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Pumpage (*n* x October 1986 rates)			
		0.5	1	2	5
		Lateral-boundary flow (Mgal/d)			
	Alabama				
1	Upper Floridan aquifer outcrop	33.6	33.8	34.9	38.6
2	Basin divide, no flow	0	0	0	0
	Florida				
3	Southwestern boundary	540.7	541	541.8	544.3
4	Southern boundary	26.6	26.8	27	27.9
5	Southeastern boundary	250.6	251.6	253.6	261
	Georgia				
6	Southeastern boundary	19.3	19.9	21.2	25.7
7	Southern Solution Escarpment	23.4	35.7	60.4	137
8	Northern Solution Escarpment	–134.8	–129.6	–119.3	–88.2
9	Northeastern boundary	160.4	163.5	169.8	189.6
10	Northern boundary	0.2	0.4	0.7	1.9
11	Upper Floridan aquifer outcrop	57.9	61.9	69.5	92.4

Table 30. Computed lateral-boundary (regional) flow rates by state from pumping scenarios R5P*n* (*n*=0.5, 1, 2, 5), Upper Floridan model, simulating dry conditions of boundary and semiconfining-unit head and stream stage at Q_{50} levels (table 1)

[Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Pumpage (*n* x October 1986 rates)			
		0.5	1	2	5
		Lateral-boundary flow (Mgal/d)			
	Alabama				
1	Upper Floridan aquifer outcrop	7	7.1	8.6	12.5
2	Basin divide, no flow	0	0	0	0
	Florida				
3	Southwestern boundary	423	423.4	424.2	426.9
4	Southern boundary	−38.1	−37.9	−37.6	−36.7
5	Southeastern boundary	171.8	172.8	174.8	182.7
	Georgia				
6	Southeastern boundary	−15.1	−14.5	−13.3	−8.5
7	Southern Solution Escarpment	−46.8	−34.5	-9.6	67.5
8	Northern Solution Escarpment	−132.8	−127.6	−117.1	−85.6
9	Northeastern boundary	156.4	159.6	166.2	187.5
10	Northern boundary	0	0.2	0.6	1.8
11	Upper Floridan aquifer outcrop	111.7	116	123.5	147.2

Table 31. Computed lateral-boundary (regional) flow rates by state from pumping scenarios R6P*n* (*n*=0.5, 1, 2, 5), Upper Floridan model, simulating normal conditions of boundary and semiconfining-unit head and stream stage at Q_{50} levels (table 1)

[Mgal/d, million gallons per day]

Boundary segment (fig. 24)	Description	Pumpage (*n* x October 1986 rates)			
		0.5	1	2	5
		Lateral-boundary flow (Mgal/d)			
	Alabama				
1	Upper Floridan aquifer outcrop	32.3	32.7	34.1	38.5
2	Basin divide, no flow	0	0	0	0
	Florida				
3	Southwestern boundary	531.5	531.9	532.6	535.1
4	Southern boundary	15.4	15.5	15.8	16.7
5	Southeastern boundary	243	244	246	253.4
	Georgia				
6	Southeastern boundary	16.3	16.9	18.2	22.7
7	Southern Solution Escarpment	10.7	23	47.7	124.1
8	Northern Solution Escarpment	–141.8	–136.6	–126.3	–95.1
9	Northeastern boundary	158.9	162	168.3	188.6
10	Northern boundary	0.1	0.3	0.7	1.8
11	Upper Floridan aquifer outcrop	55.6	59.5	66.8	89

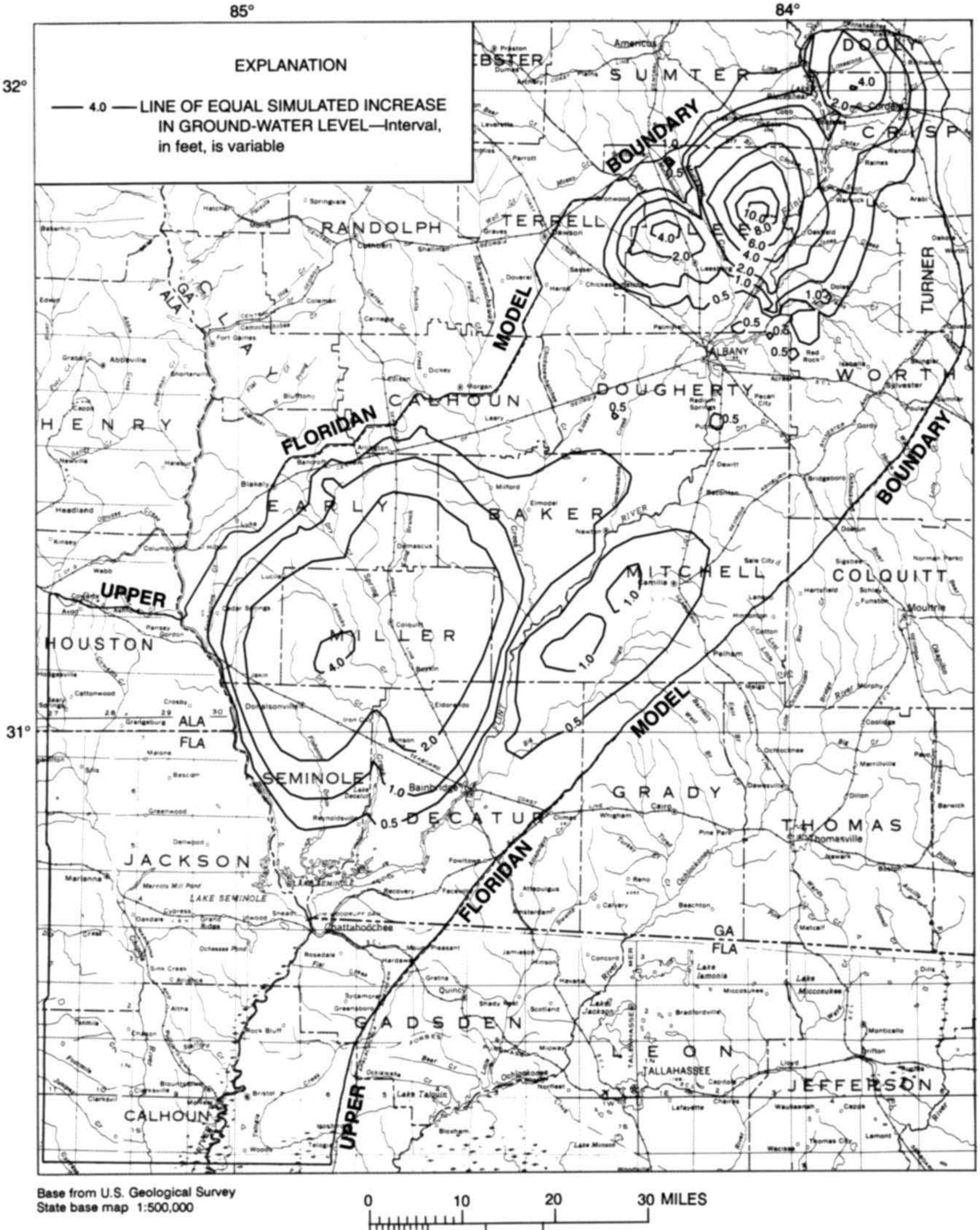


Figure 25. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 0.5, stream stage at October 1986 levels, and dry conditions of boundary and semiconfining-unit head.

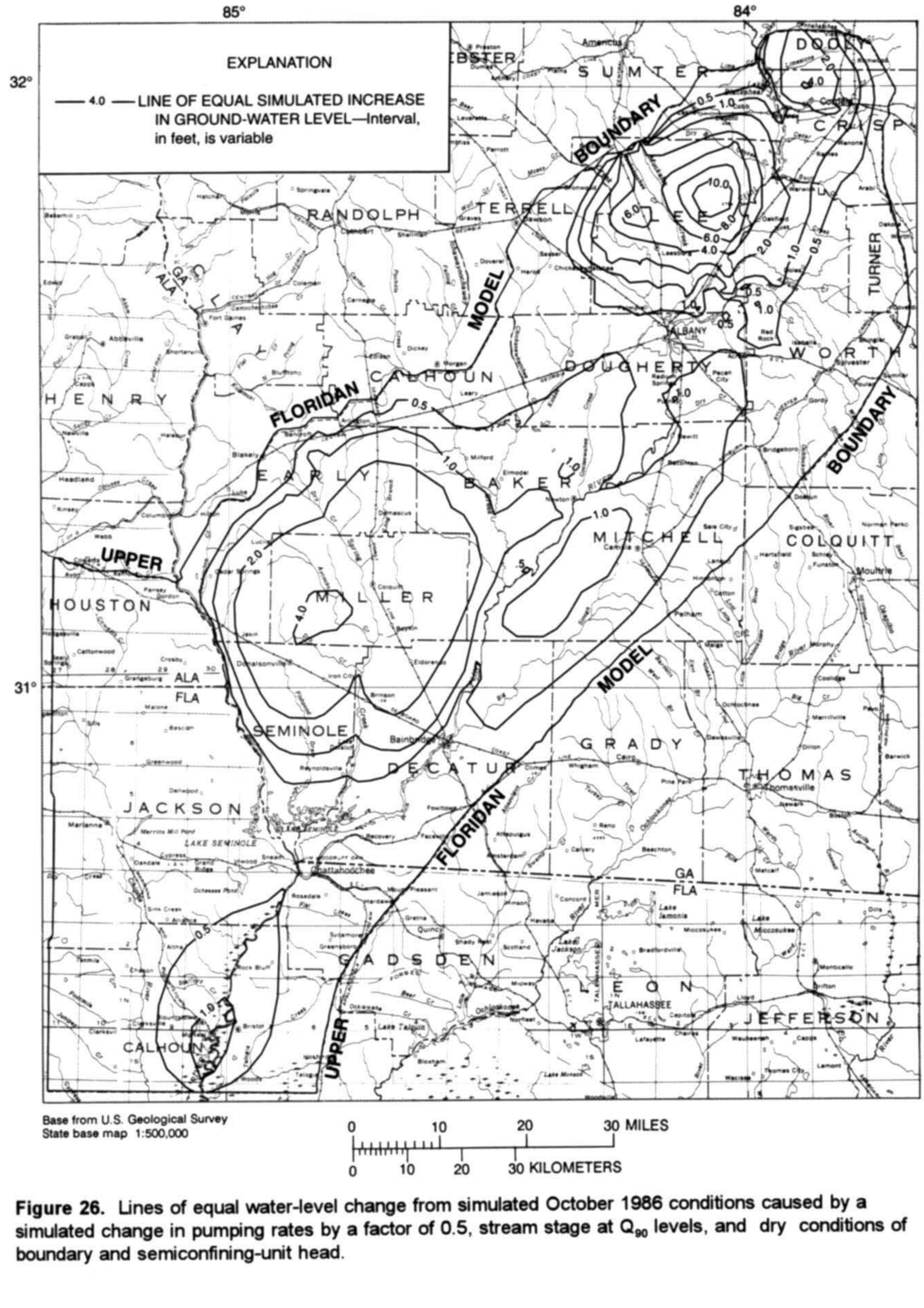


Figure 26. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 0.5, stream stage at Q_{90} levels, and dry conditions of boundary and semiconfining-unit head.

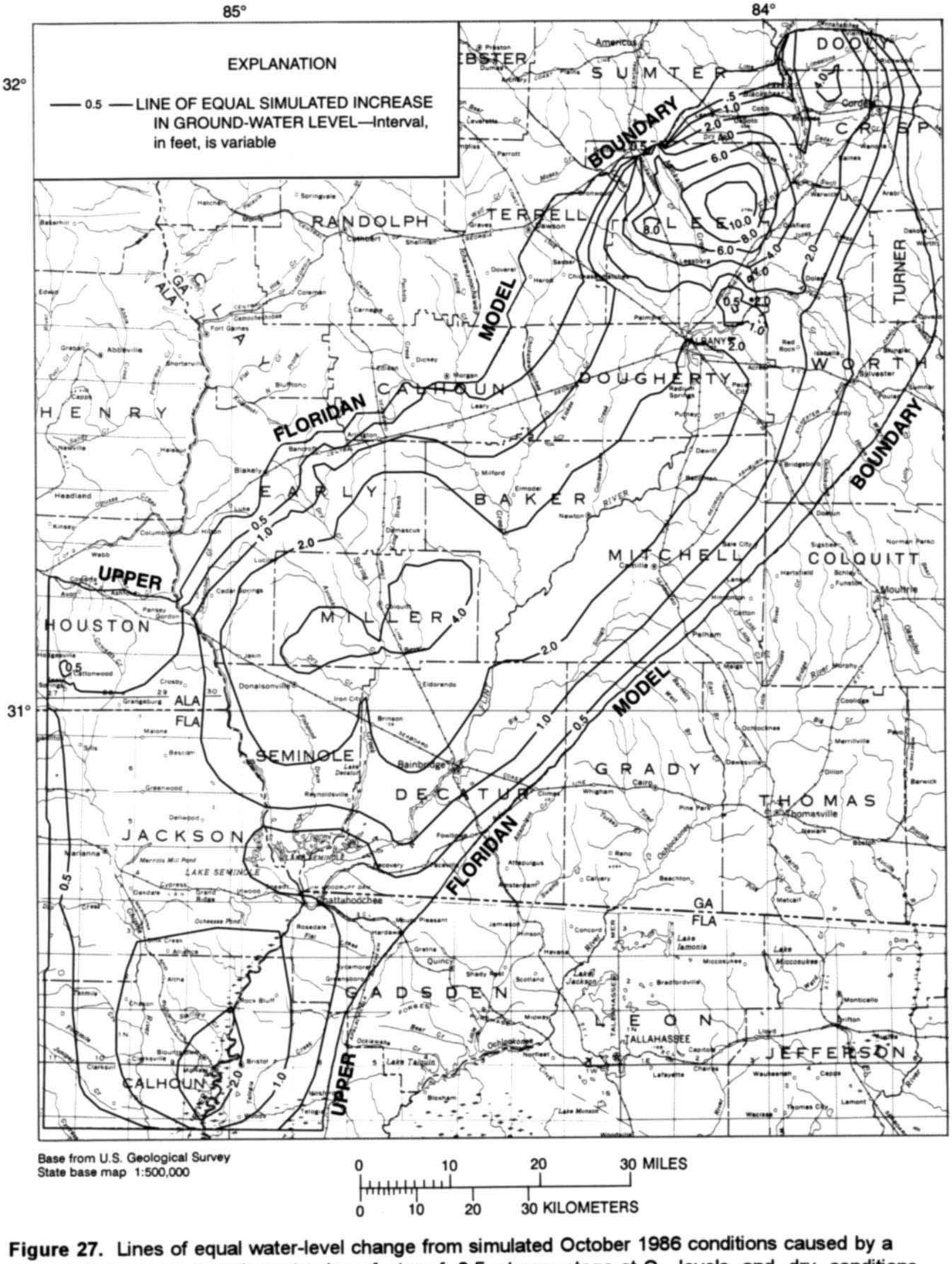


Figure 27. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 0.5, stream stage at Q_{50} levels, and dry conditions of boundary and semiconfining-unit head.

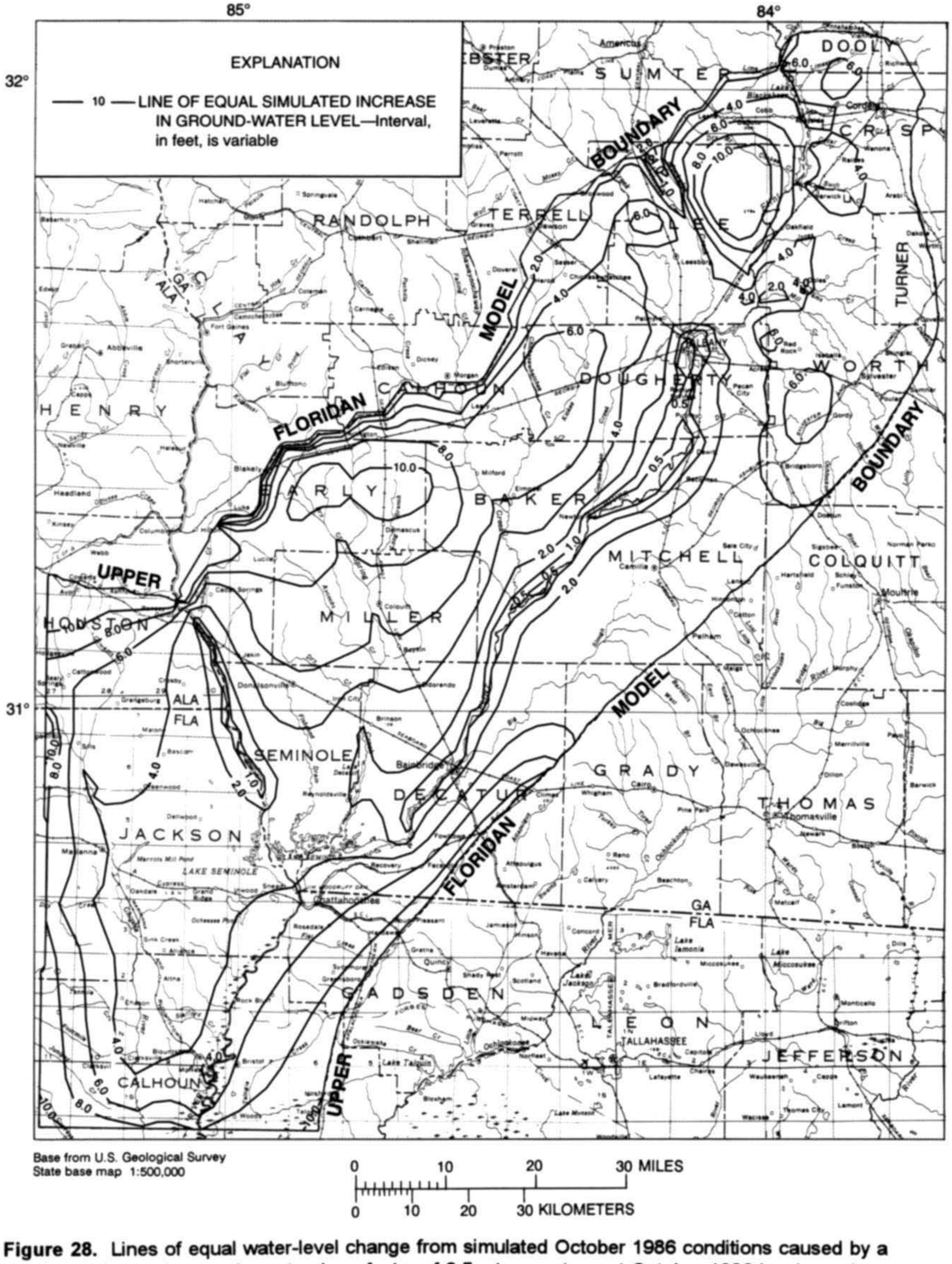


Figure 28. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 0.5, stream stage at October 1986 levels, and normal conditions of boundary and semiconfining-unit head.

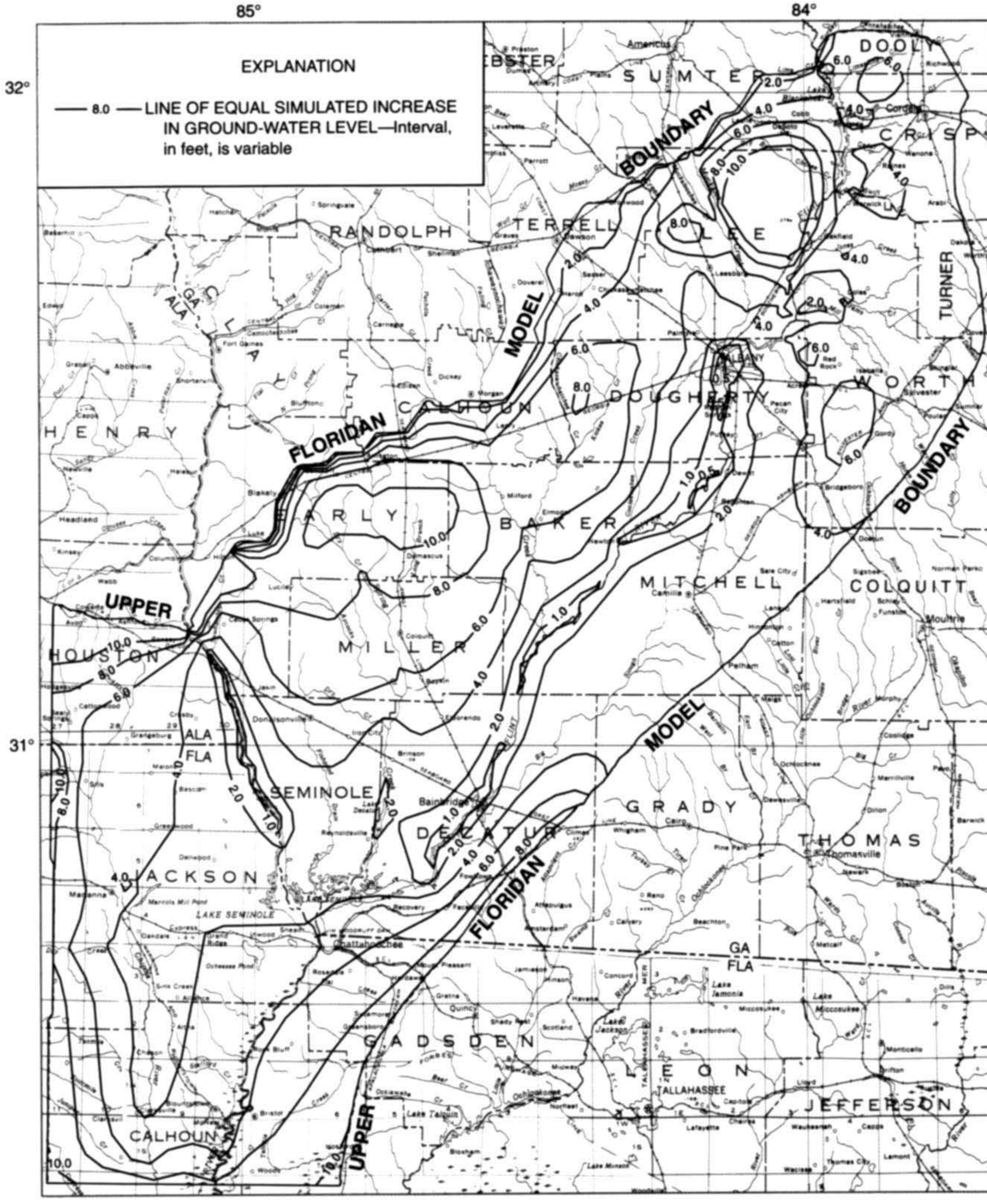


Figure 29. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 0.5, stream stage at Q_{90} levels, and normal conditions of boundary and semiconfining-unit head.

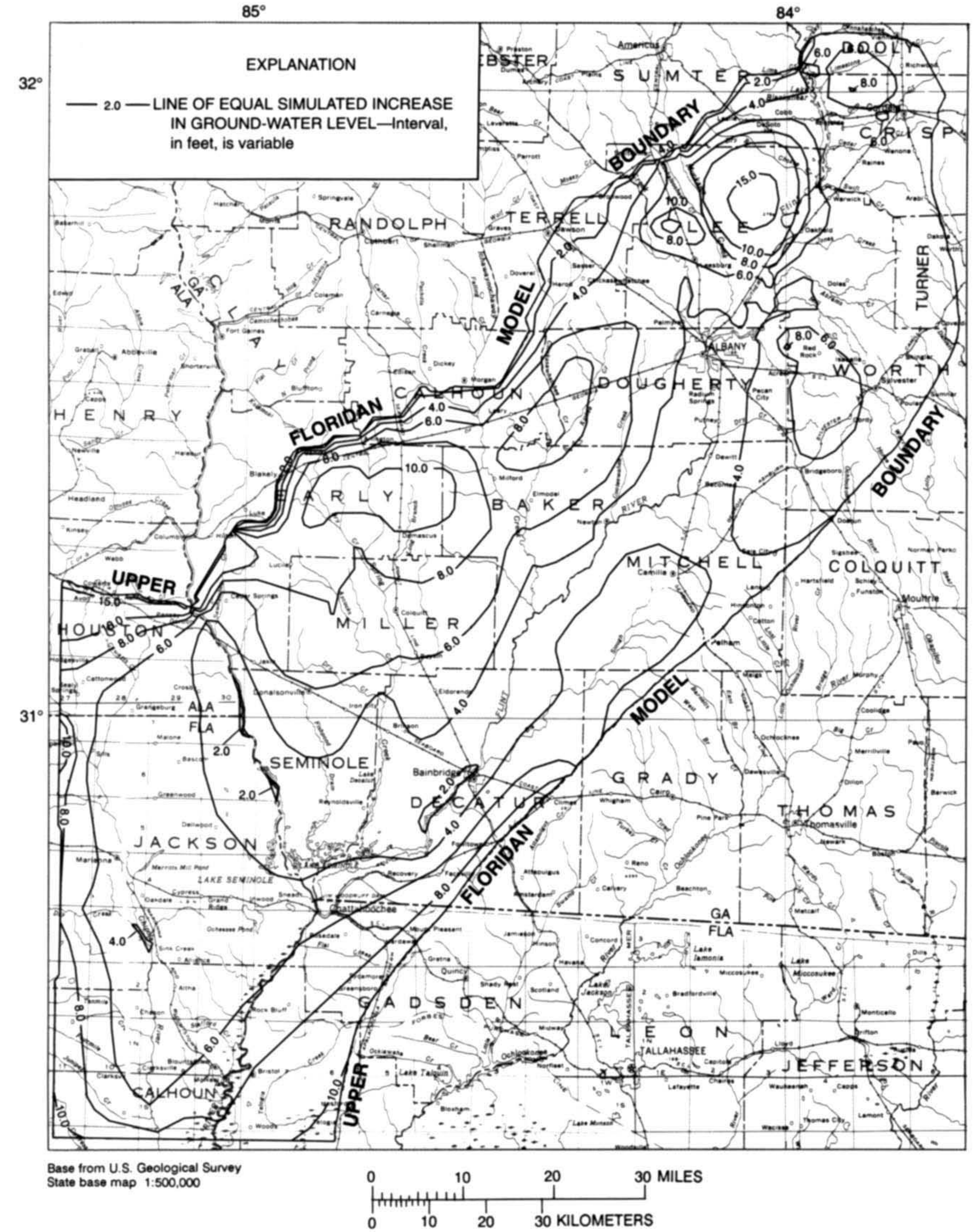


Figure 30. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 0.5, stream stage at Q_{50} levels, and normal conditions of boundary and semiconfining-unit head.

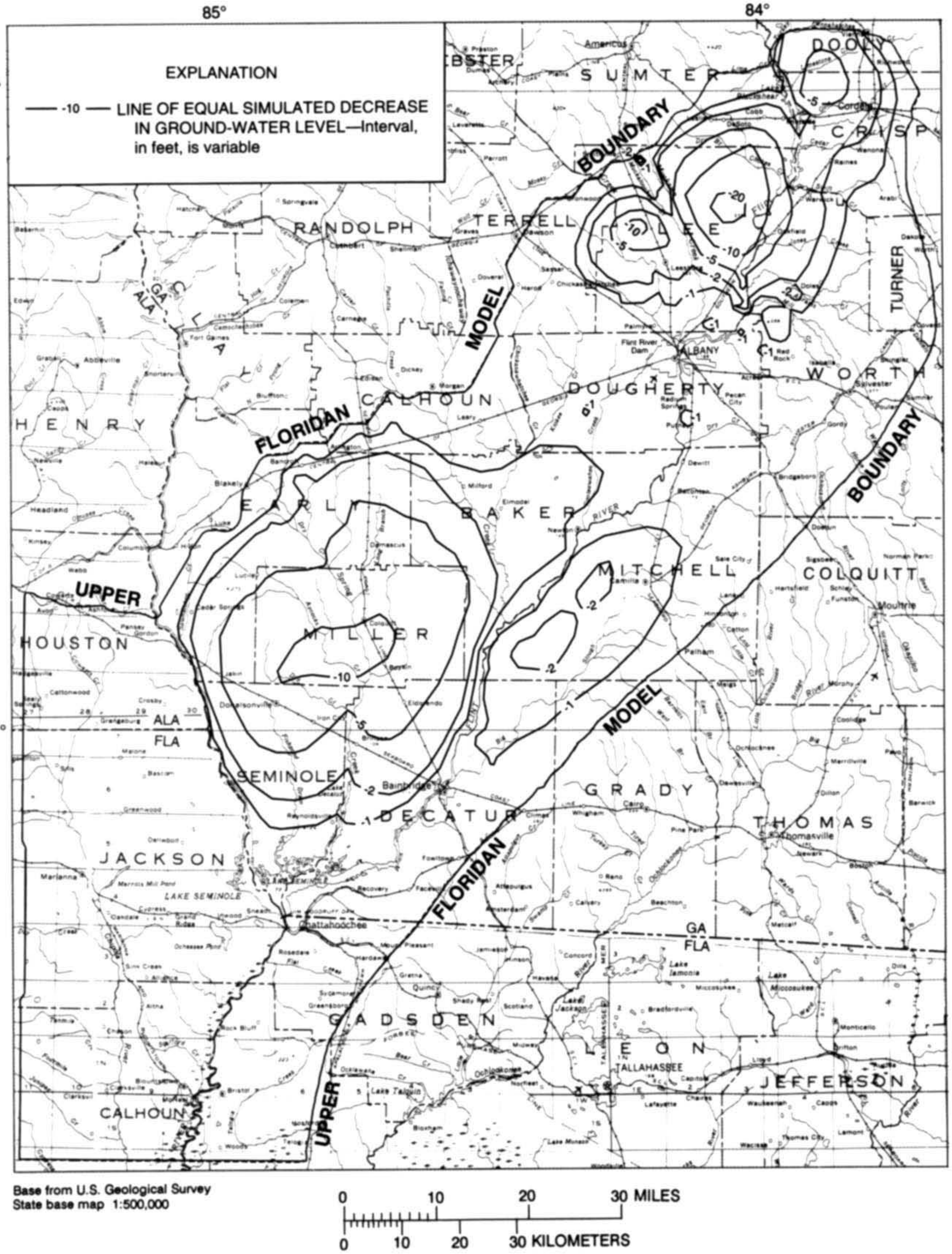


Figure 31. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 2, stream stage at October 1986 levels, and dry conditions of boundary and semiconfining-unit head (modified from Torak and others, 1996).

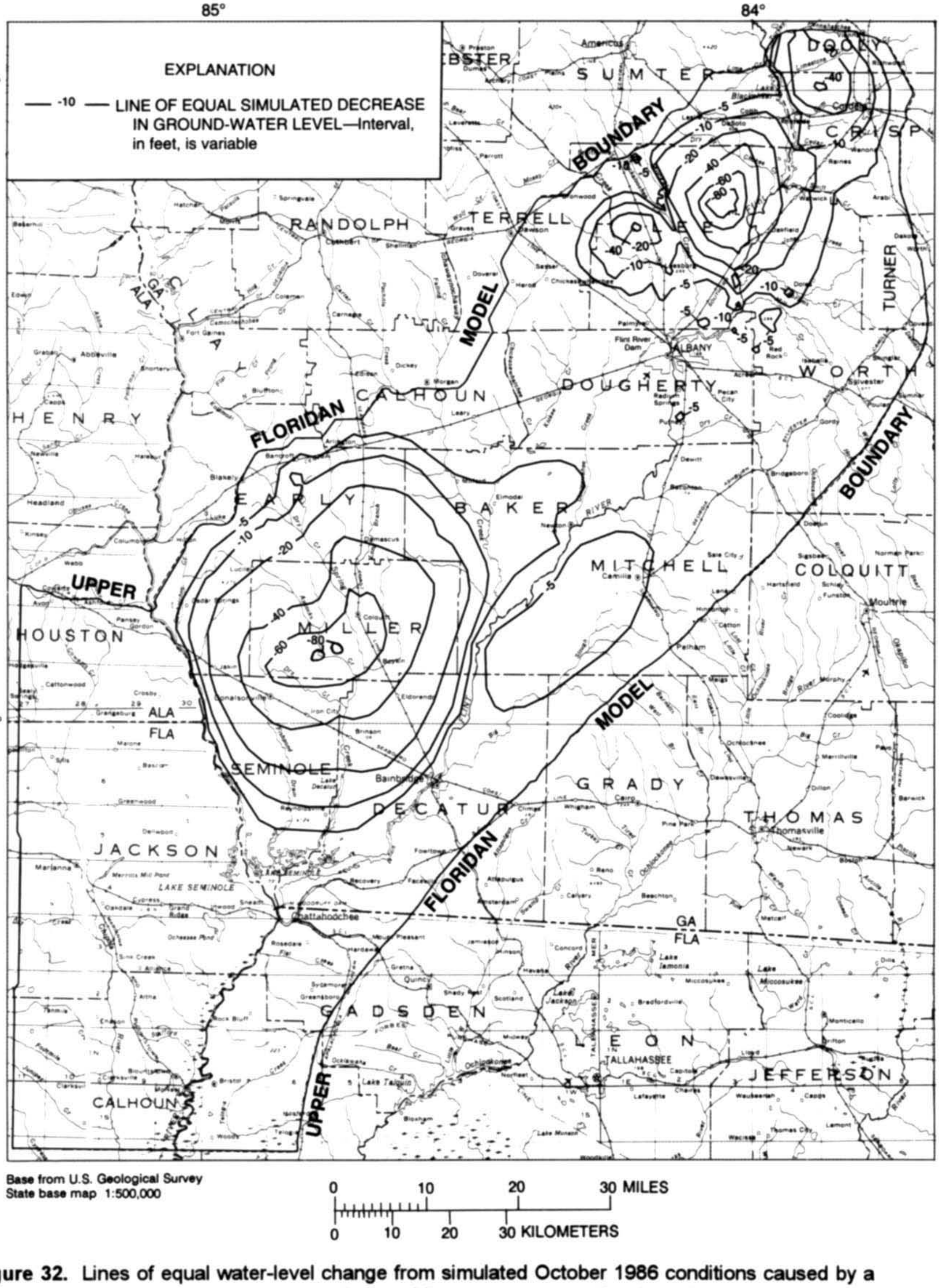


Figure 32. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 5, stream stage at October 1986 levels, and dry conditions of boundary and semiconfining-unit head (modified from Torak and others, 1996).

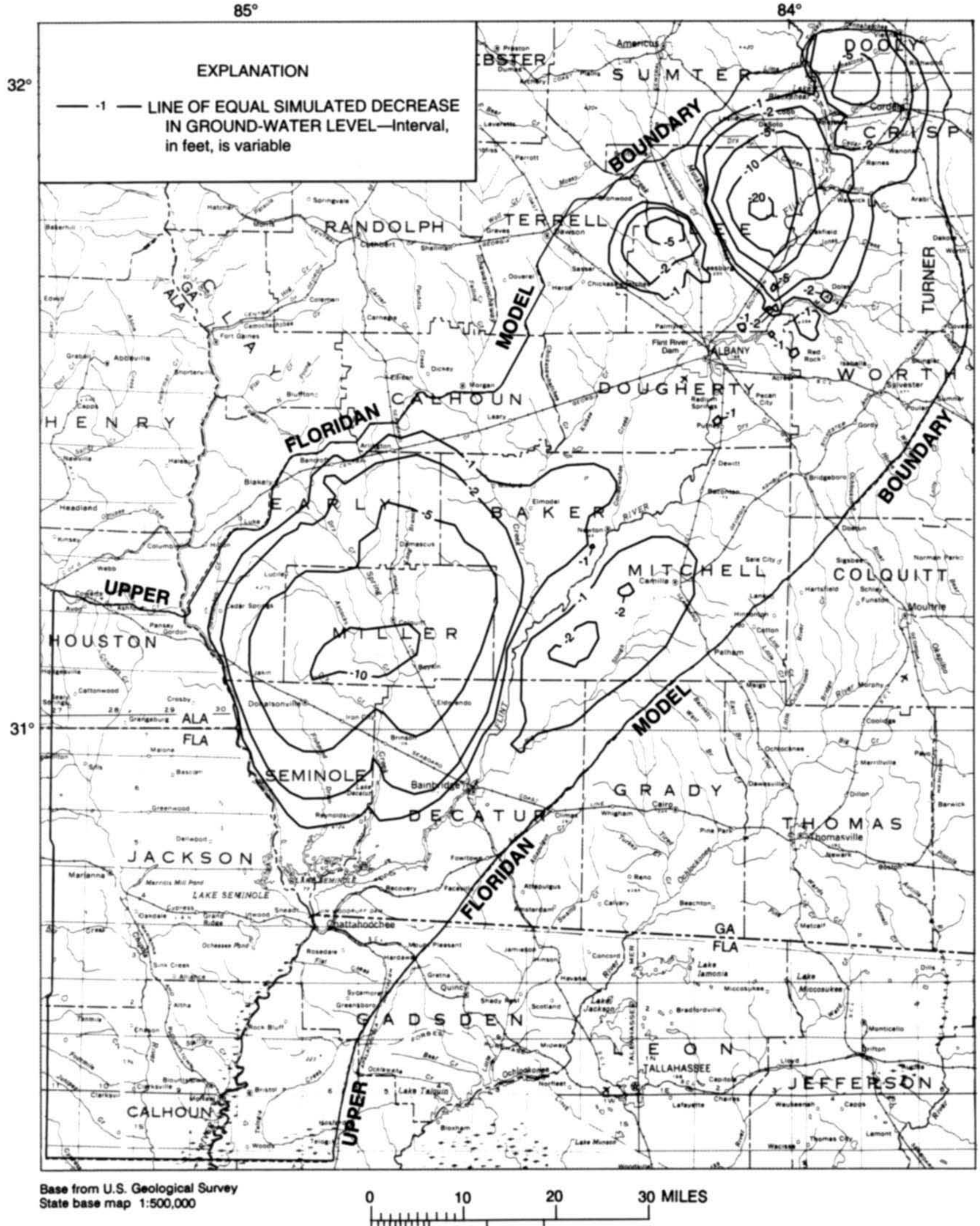


Figure 33. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 2, stream stage at Q_{90} levels, and dry conditions of boundary and semiconfining-unit head.

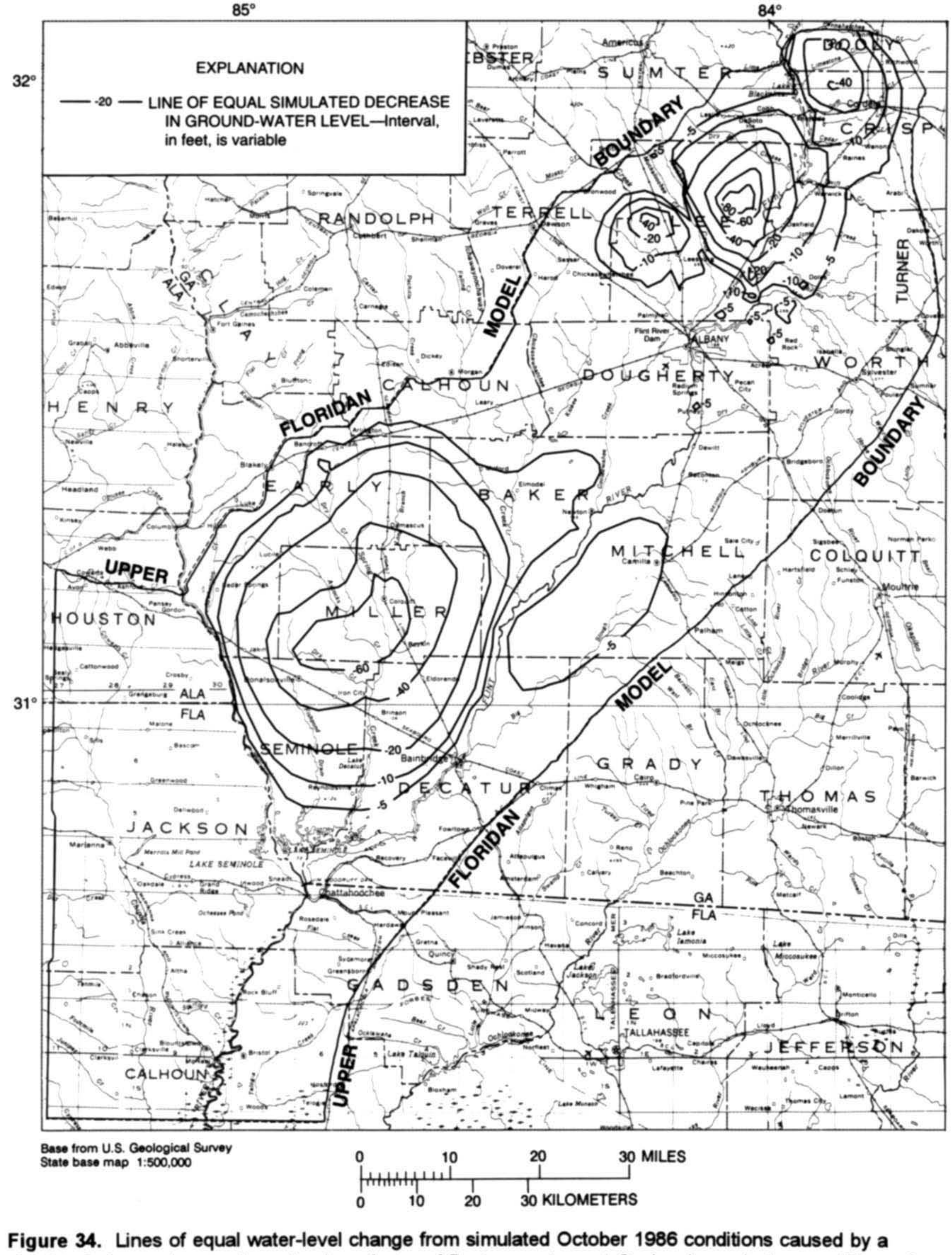


Figure 34. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 5, stream stage at Q_{90} levels, and dry conditions of boundary and semiconfining-unit head.

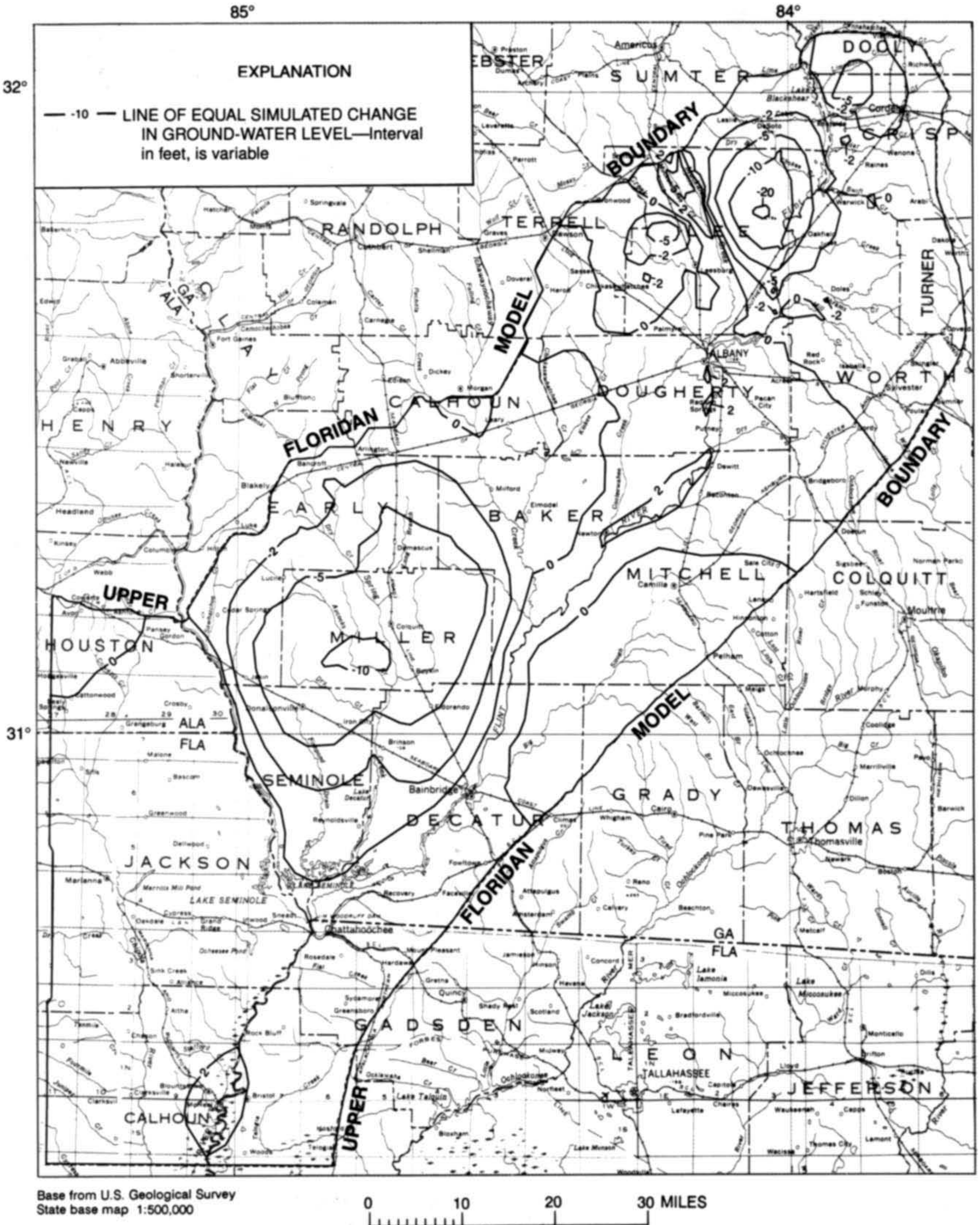


Figure 35. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 2, stream stage at Q_{50} levels, and dry conditions of boundary and semiconfining-unit head.

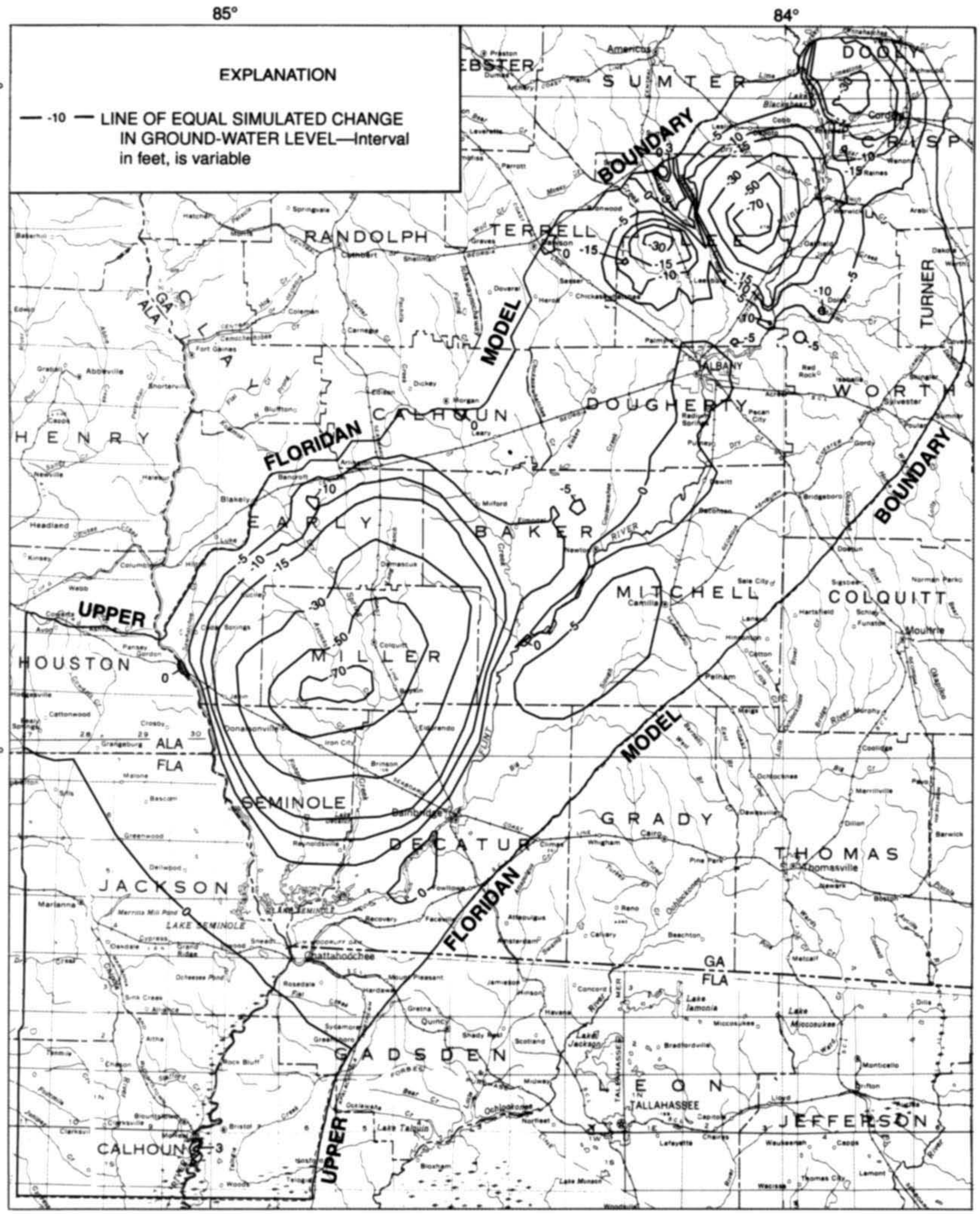


Figure 36. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 5, stream stage at Q_{50} levels, and dry conditions of boundary and semiconfining-unit head.

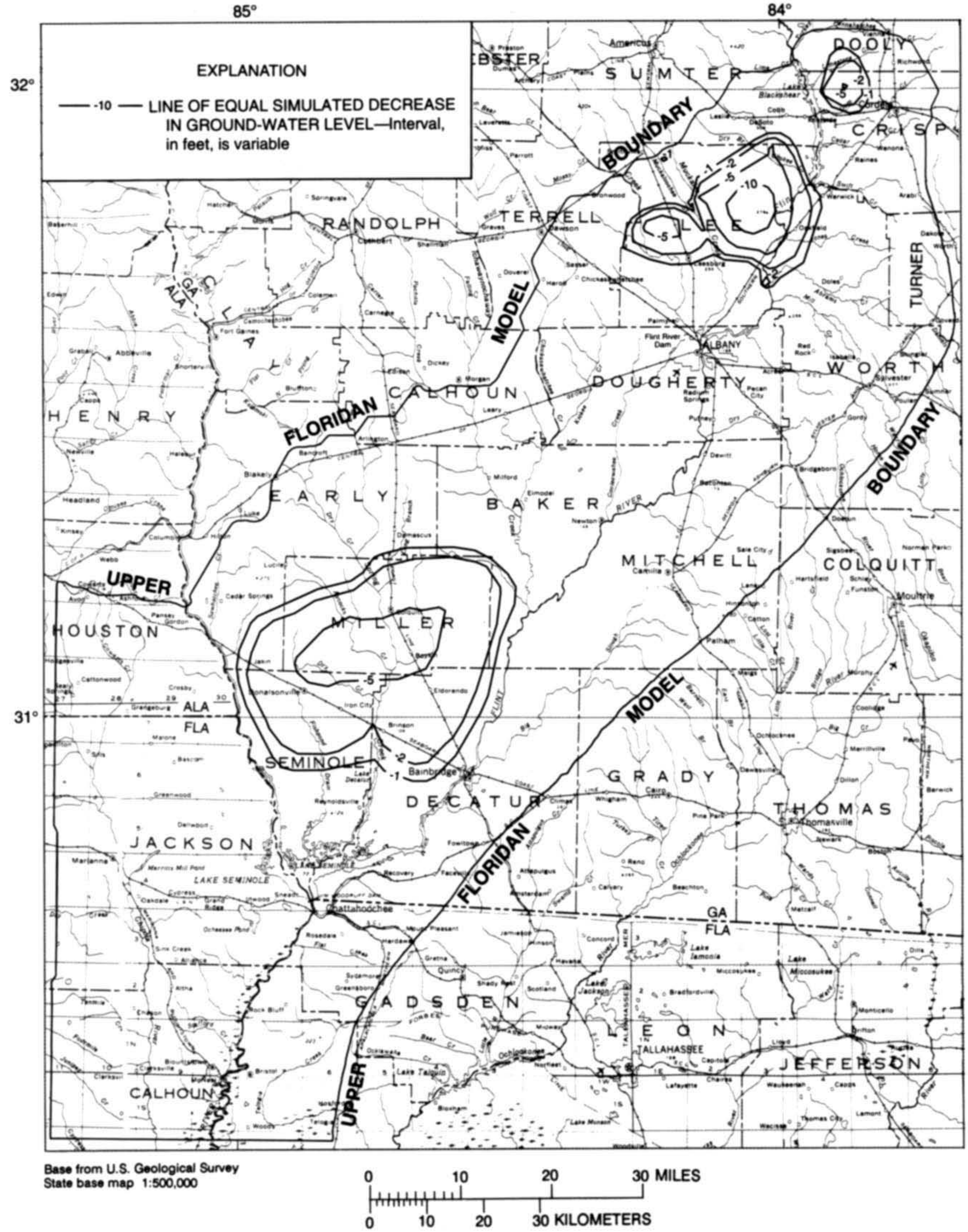


Figure 37. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 2, stream stage at October 1986 levels, and normal conditions of boundary and semiconfining-unit head.

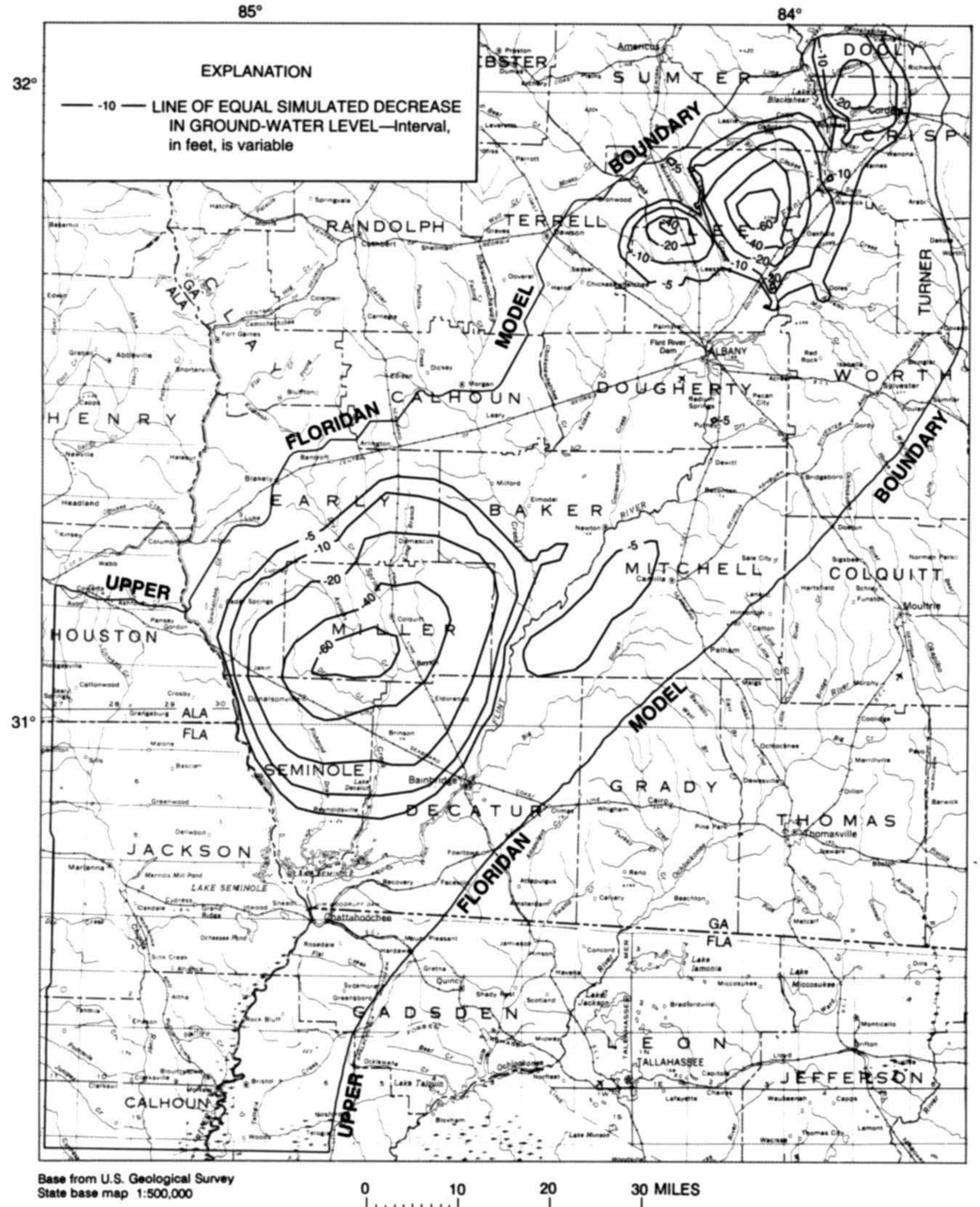


Figure 38. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 5, stream stage at October 1986 levels, and normal conditions of boundary and semiconfining-unit head.

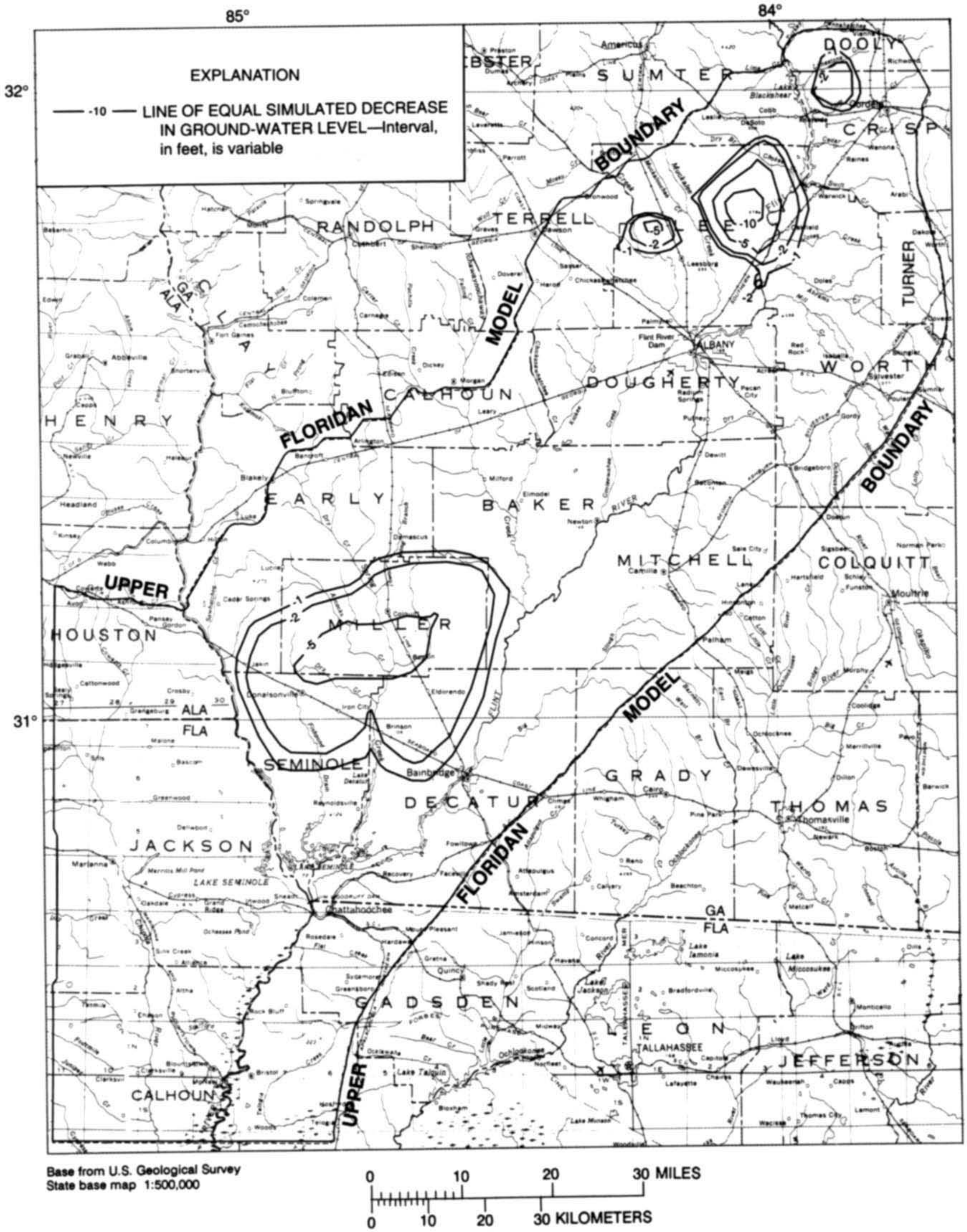


Figure 39. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 2, stream stage at Q_{90} levels, and normal conditions of boundary and semiconfining-unit head.

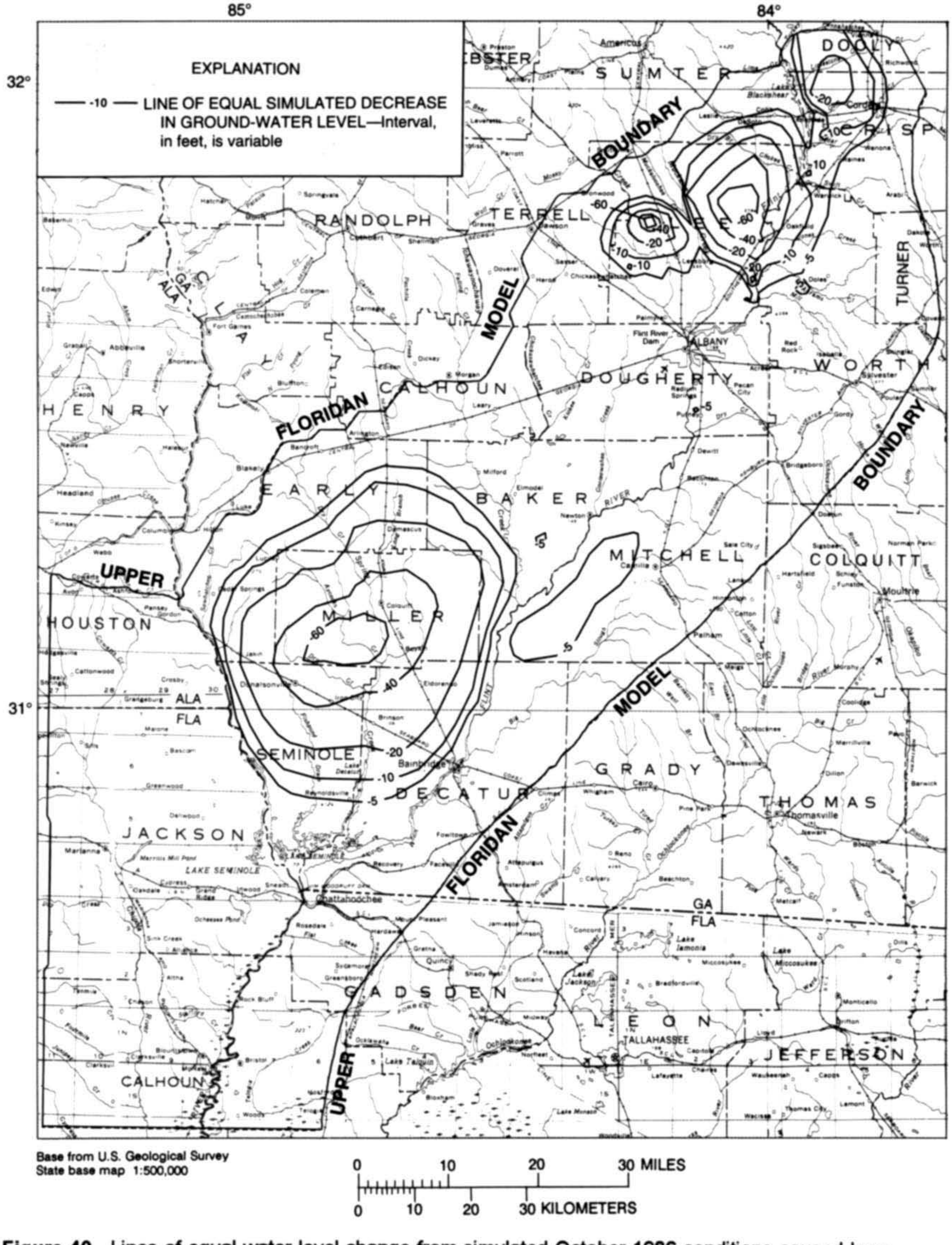


Figure 40. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 5, stream stage at Q_{90} levels, and normal conditions of boundary and semiconfining-unit head.

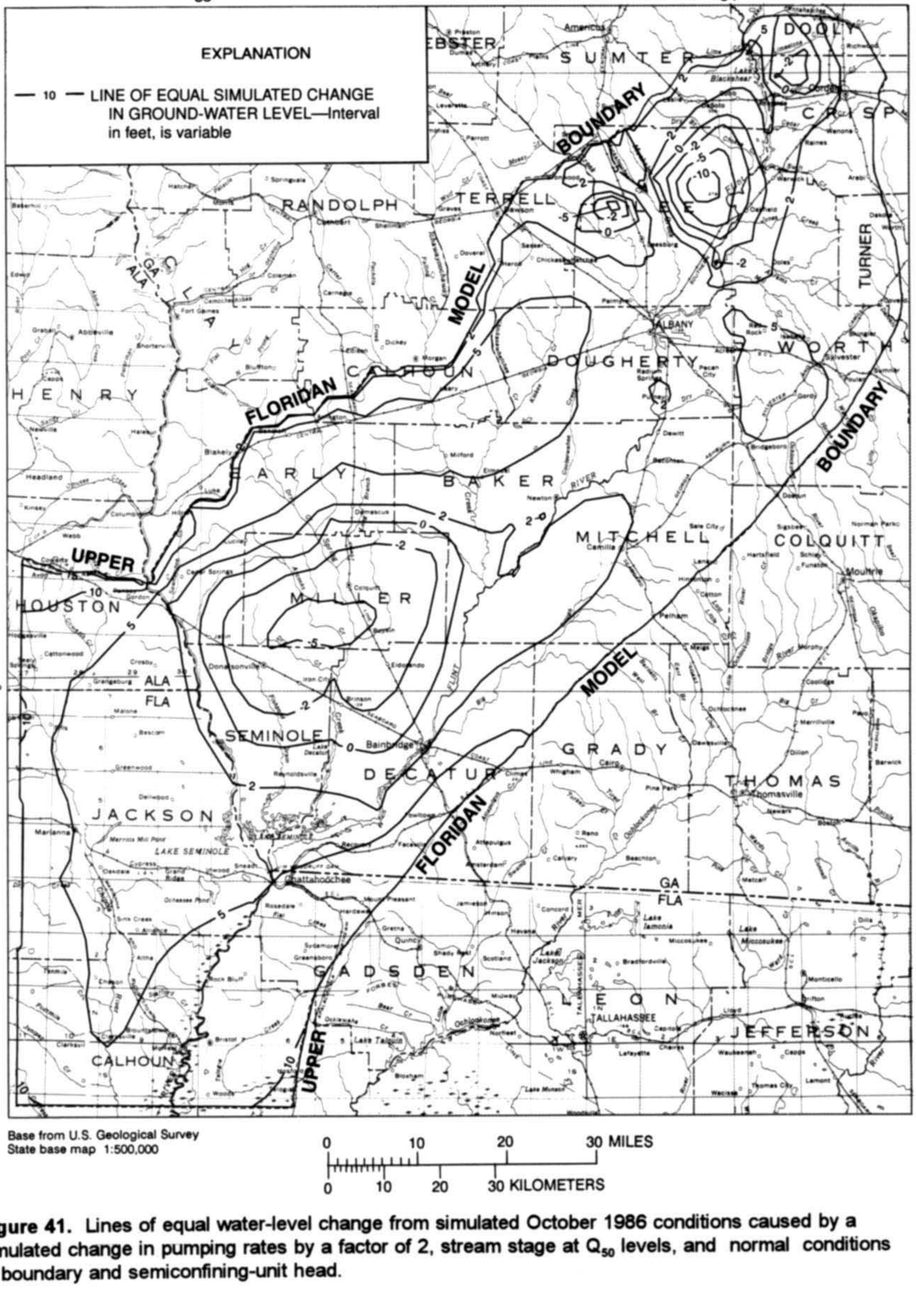


Figure 41. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 2, stream stage at Q_{50} levels, and normal conditions of boundary and semiconfining-unit head.

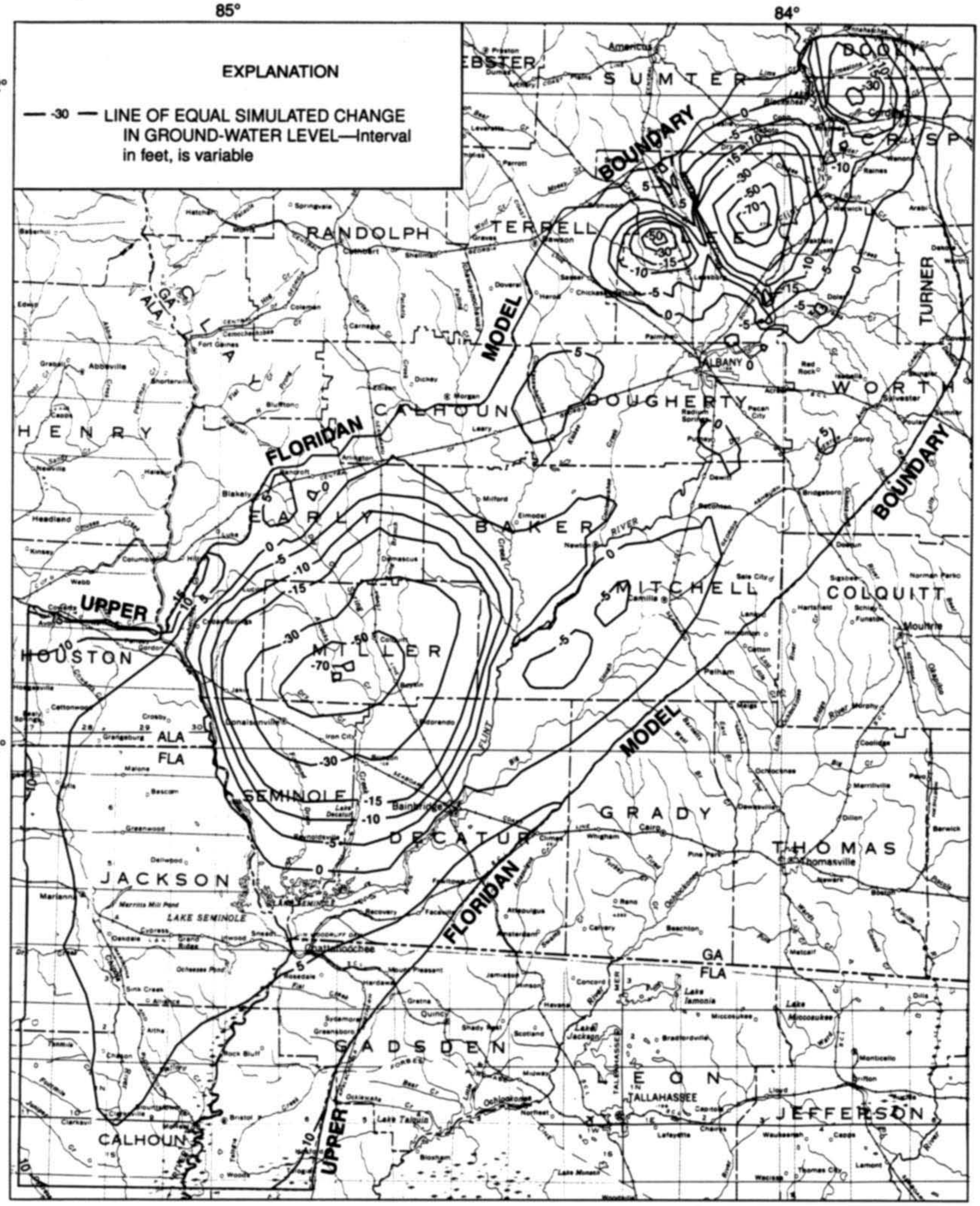
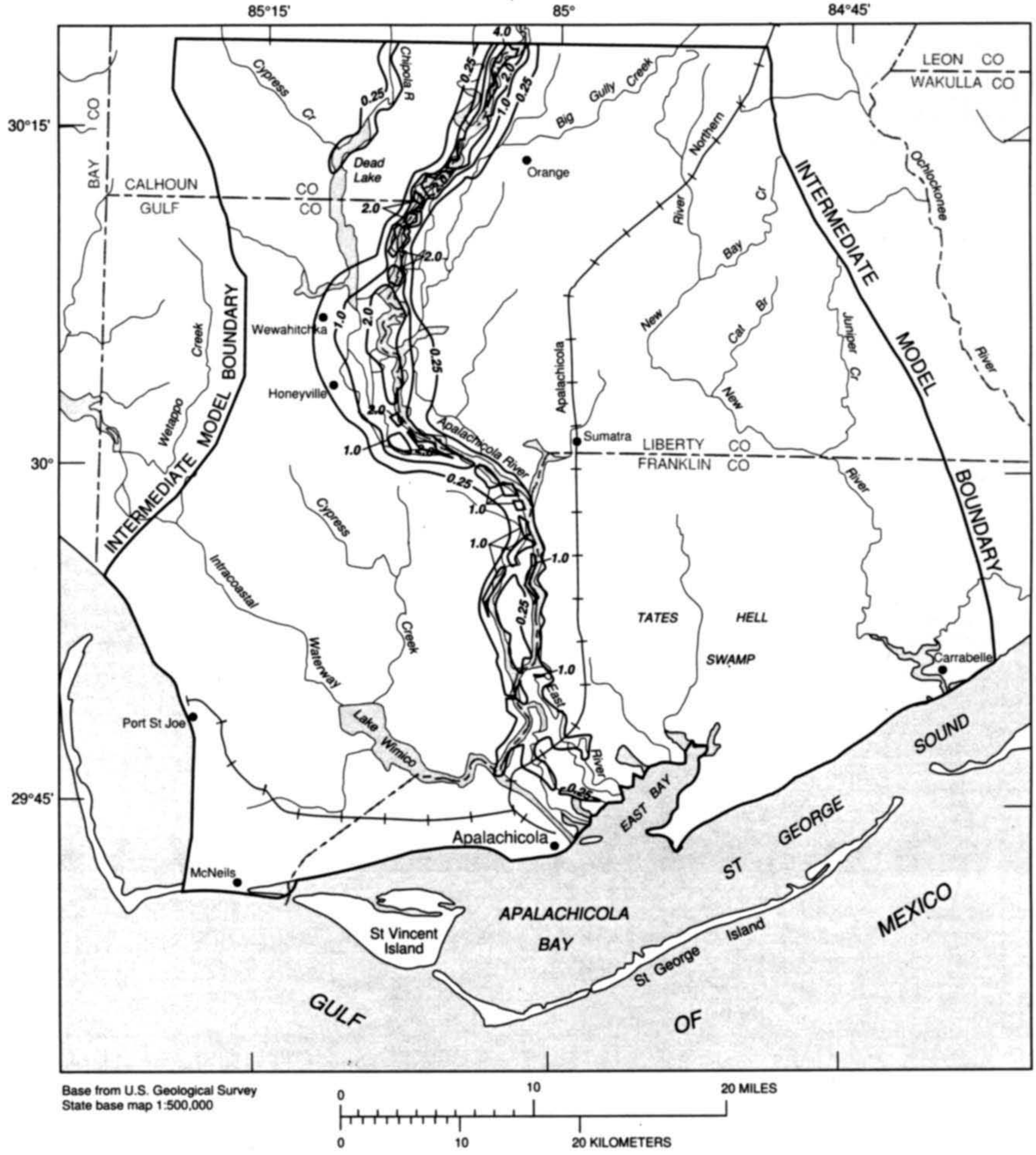


Figure 42. Lines of equal water-level change from simulated October 1986 conditions caused by a simulated change in pumping rates by a factor of 5, stream stage at Q_{50} levels, and normal conditions of boundary and semiconfining-unit head.



EXPLANATION

— 0.25 — LINE OF EQUAL SIMULATED WATER-LEVEL INCREASE—Interval, in feet, is variable

Figure 44. Lines of equal water-level change from simulated October 1986 conditions in the Intermediate system caused by a simulated change in stream stage to Q_{50} levels and dry conditions of boundary and semiconfining-unit head.

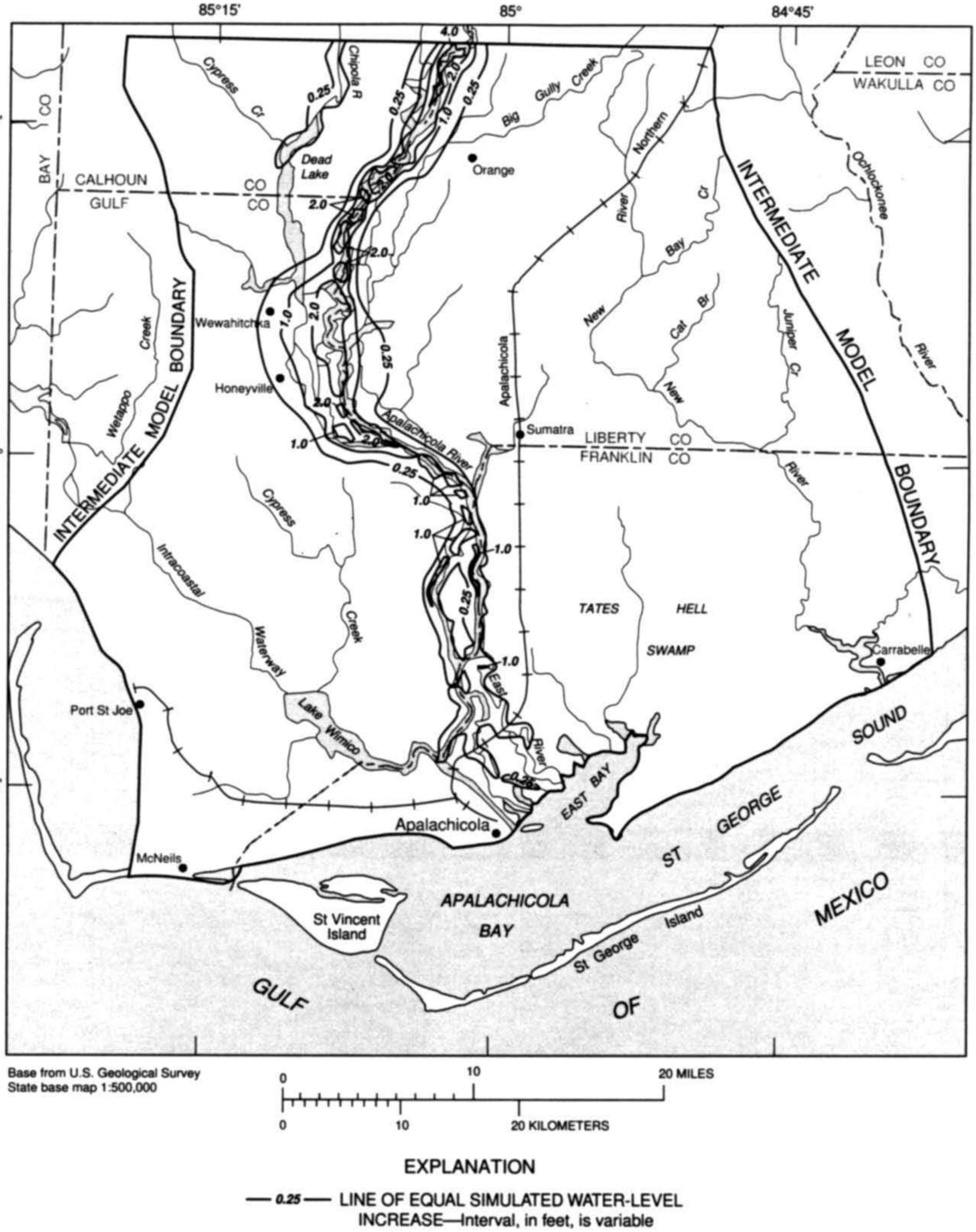
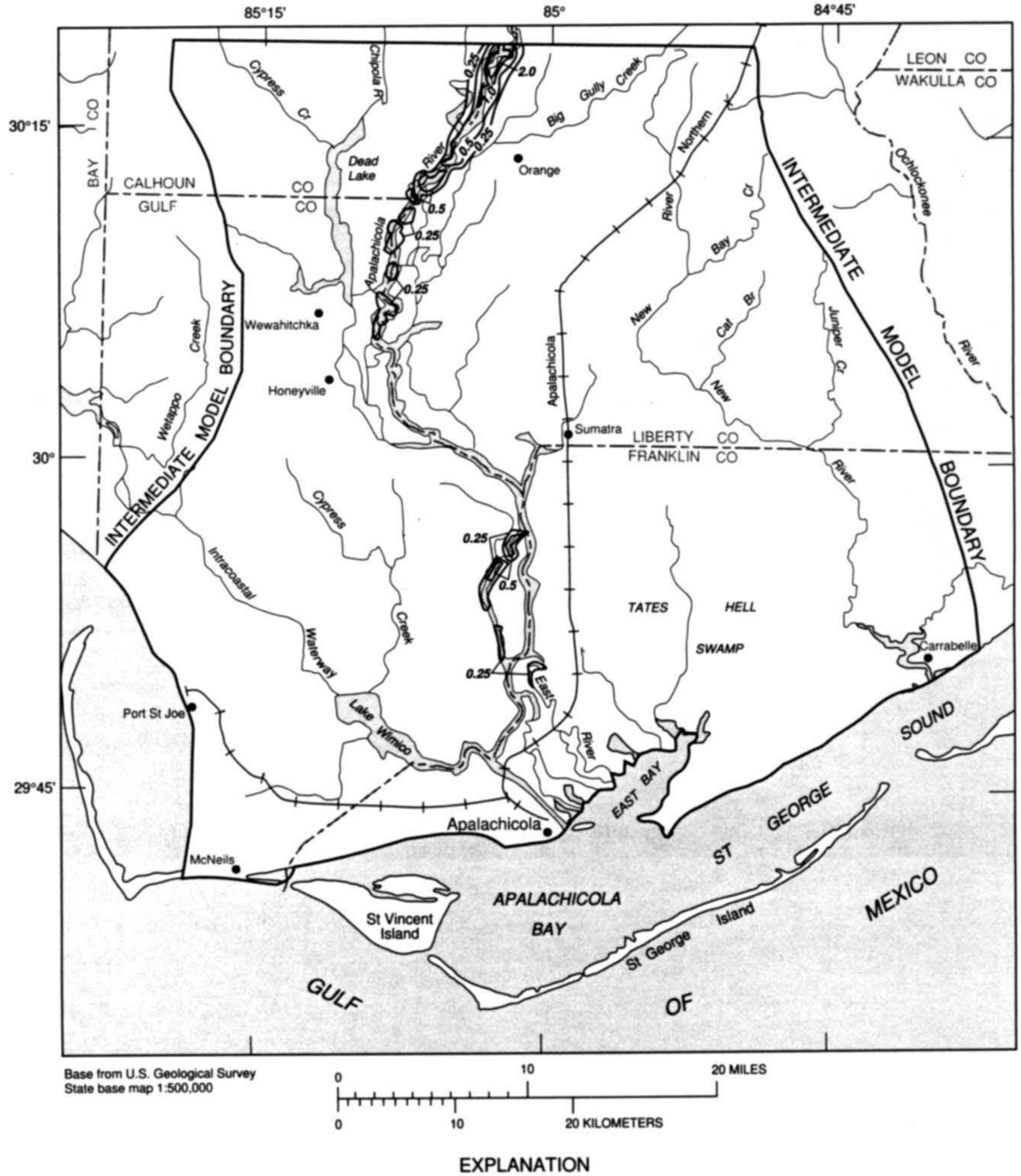


Figure 45. Lines of equal water-level change from simulated October 1986 conditions in the Intermediate system caused by a simulated change in stream stage to Q_{50} levels and normal conditions of boundary and semiconfining-unit head.



EXPLANATION

— 0.25 — LINE OF EQUAL SIMULATED WATER-LEVEL INCREASE—Interval, in feet, is variable

Figure 46. Lines of equal water-level change from simulated October 1986 conditions in the Intermediate system caused by a simulated change in stream stage to Q_{90} levels and dry conditions of boundary and semiconfining-unit head.

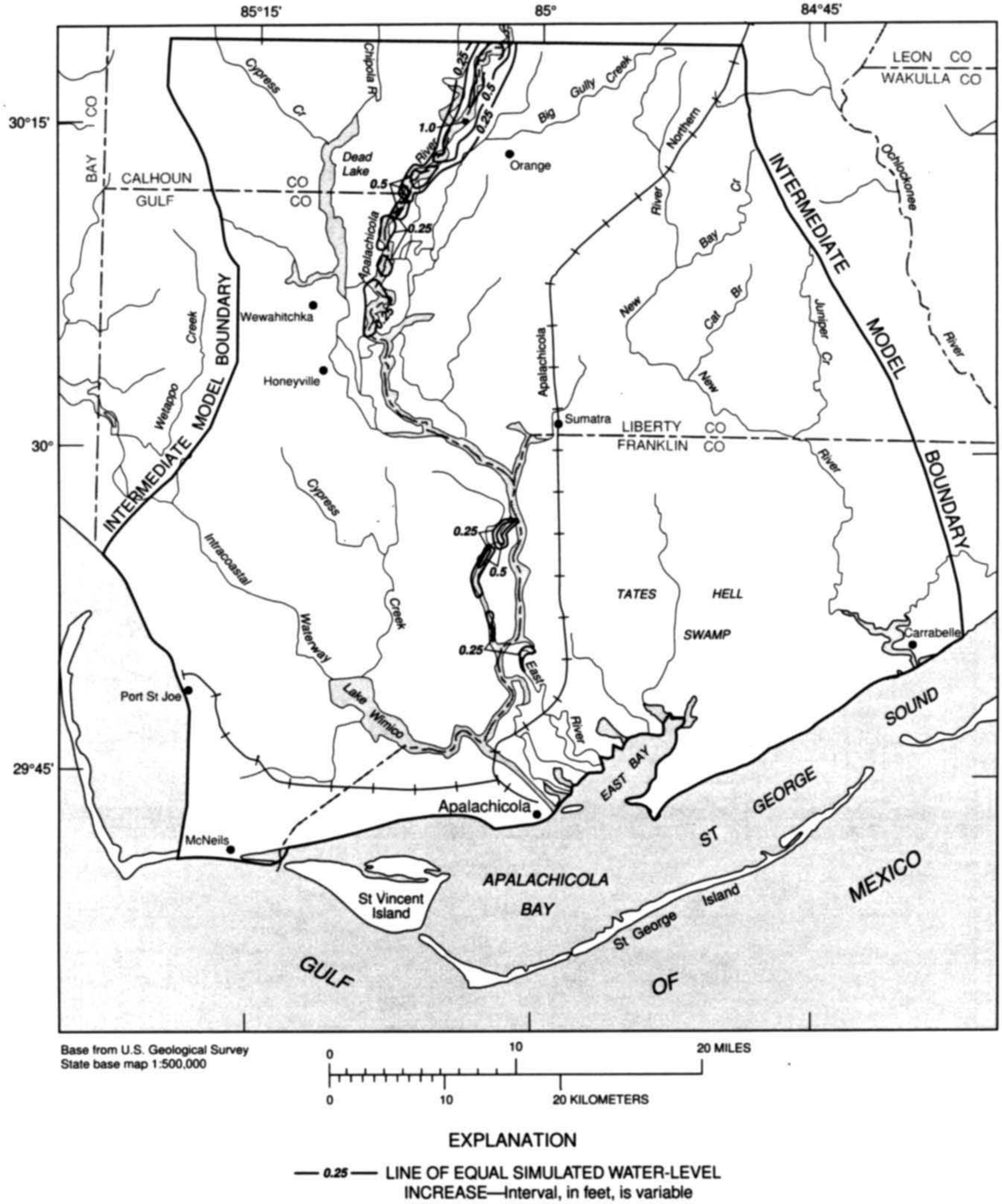
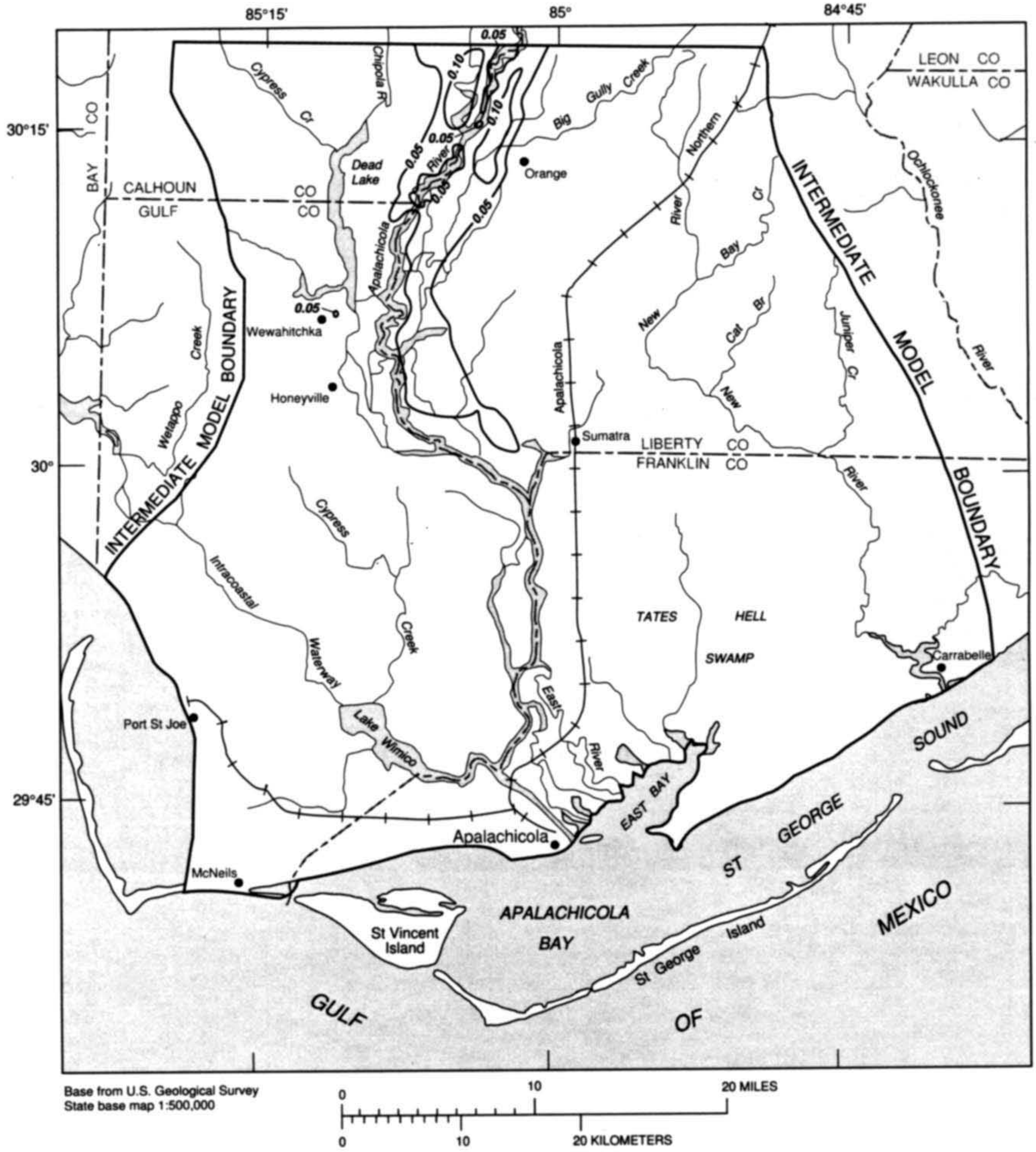


Figure 47. Lines of equal water-level change from simulated October 1986 conditions in the Intermediate system caused by a simulated change in stream stage to Q_{90} levels and normal conditions of boundary and semiconfining-unit head.



EXPLANATION

— 0.10 — LINE OF EQUAL SIMULATED WATER-LEVEL INCREASE—Interval, in feet, is variable

Figure 48. Lines of equal water-level change from simulated October 1986 conditions in the Intermediate system caused by simulated change in boundary and semiconfining-unit head to normal conditions.

APPENDIX A

Table A1. Ground-water-level residuals from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin

[Water-level altitude and residual, in feet above sea level]

Well number	$h_{i\ model}$[1] Computed water–level altitude	$h_{i\ obs.}$[1] Measured water–level altitude	Water–level residual	Well number	$h_{i\ model}$[1] Computed water–level altitude	$h_{i\ obs.}$[1] Measured water–level altitude	Water–level residual
CAL002	44.9	47.8	–2.9	06G012	91.1	99.9	–8.8
CAL001	51.7	57.8	–6.1	11G001	97.1	91.7	5.4
GAD003	71.1	57.4	13.7	10G001	95.4	96.6	–1.2
JAC001	72.7	70.6	2.1	ALA0V4	95.2	113.6	–18.4
JAC002	75.6	86.3	–10.7	08G005	89.0	94.1	–5.1
06E001	76.6	72.1	4.5	10G005	88.6	86.5	2.1
JAC006	76.8	87.2	–10.4	11G003	103.7	96.7	7.0
JAC009	79.1	72.4	6.7	ALA0S8	131.4	136.2	–4.8
08E005	75.9	73.8	2.1	09G007	82.0	81.8	.2
08E003	76.1	73.0	3.1	08G007	88.6	100.1	–11.5
06E020	76.8	80.4	–3.6	11G004	106.9	105.2	1.7
06E018	77.0	72.5	4.5	07G005	97.5	90.7	6.8
08E006	76.4	76.4	0.0	09G010	84.7	86.8	–2.1
07E007	77.1	72.4	4.7	ALA0U8	129.6	136.4	–6.8
06E019	77.0	74.1	2.9	ALAT10	136.1	124.4	11.7
07E006	77.3	77.7	–.4	06G008	95.0	92.1	2.9
08E002	76.5	78.8	–2.3	07G008	99.4	97.5	1.9
08E007	76.6	72.3	4.3	09G008	91.6	97.3	–5.7
07F005	78.3	75.9	2.4	06G006	95.9	90.3	5.6
07F006	79.1	73.2	5.9	11G002	103.7	104.0	–.3
06F007	77.7	77.5	.2	10G313	90.4	88.7	1.7
08F009	77.0	77.1	–.1	09G005	91.2	99.8	–8.6
06F004	79.5	78.7	.8	08G004	103.9	103.2	.7
06F001	79.1	74.9	4.2	09G004	82.9	78.6	4.3
08F017	77.6	79.4	–1.8	08G001	103.6	110.6	–7.0
06F005	79.6	85.6	–6.0	09G006	99.3	92.1	7.2
08F012	78.1	77.4	.7	12H009	121.9	120.2	1.7
07F002	82.7	85.0	–2.3	07G001	119.2	117.0	2.2
06F003	82.8	81.5	1.3	07H006	116.3	121.0	–4.7
08F010	79.4	77.9	1.5	06H007	119.7	124.1	–4.4
09F005	78.6	75.0	3.6	07H009	123.6	127.9	–4.3
09F520	79.4	78.7	.7	11H005	105.0	102.8	2.2
JAC003	106.5	101.5	5.0	07H005	114.4	122.5	–8.1
09F004	82.8	83.6	–.8	06H013	123.4	131.5	–8.1
07F003	82.4	69.9	12.5	09H013	101.7	104.1	–2.4
10F004	88.3	89.2	–.9	10H006	91.5	94.5	–3.0
JAC005	95.6	97.4	–1.8	06H006	125.9	129.2	–3.3
08F006	82.9	78.0	4.9	07H008	124.6	126.4	–1.8
09F006	78.6	78.7	–.1	11H003	103.8	103.6	.2
08F011	83.8	87.0	–3.2	09H012	96.2	95.9	.3
07F004	86.7	79.9	6.8	09H001	89.6	108.0	–18.4
10F001	85.3	87.5	–2.2	06H005	130.6	141.8	–11.2
08F007	84.4	84.6	–.2	07H014	131.1	129.6	1.5
06F006	88.7	89.8	–1.1	08H011	121.7	116.2	5.5
07G007	90.5	98.5	–8.0	06H004	130.1	141.6	–11.5
ALA0X2	109.8	109.7	.1	08H010	116.9	118.4	–1.5
08G006	86.1	82.3	3.8	07H002	133.4	133.7	–.3
06G007	81.6	84.6	–3.0	ALAO12	189.0	193.1	–4.1

Footnote at end of table

Table A1. Ground-water-level residuals from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin—Continued

[Water-level altitude and residual, in feet above sea level]

Well number	$h_{i\ model}$[1] Computed water–level altitude	$h_{i\ obs.}$[1] Measured water–level altitude	Water–level residual	Well number	$h_{i\ model}$[1] Computed water–level altitude	$h_{i\ obs.}$[1] Measured water–level altitude	Water–level residual
09H006	106.3	112.1	–5.8	08J005	79.2	95.2	–16.0
06H009	141.2	142.8	–1.6	14J020	193.6	197.5	–3.9
07H012	131.7	133.1	–1.4	14J018	184.0	184.4	–.4
05H011	135.6	138.0	–2.4	13J004	147.9	145.3	2.6
07H010	144.6	148.0	–3.4	09J012	152.0	147.8	4.2
05H008	144.7	158.5	–13.8	11J020	133.3	123.9	9.4
08H008	133.8	117.1	16.7	12J003	129.1	131.8	–2.7
08H006	129.4	124.9	.5	11J004	141.7	137.7	4.0
08H003	136.5	125.6	10.9	14J019	204.4	201.7	2.7
10H004	100.5	110.3	–9.8	08K001	183.6	200.0	–16.4
07H011	149.7	144.9	4.8	14J022	193.4	196.9	–3.5
09H007	124.1	127.7	–3.6	12K001	138.9	136.4	2.5
12H008	131.2	126.1	5.1	09K010	175.8	185.1	–9.3
11H008	115.5	119.6	–4.1	10K004	148.3	144.7	3.6
08H005	144.4	128.0	16.4	08K013	181.3	185.3	–4.0
09H008	128.9	130.2	–1.3	11K011	141.6	137.9	3.7
08H009	139.3	145.1	–5.8	14K007	189.4	185.3	4.1
09H009	120.8	126.6	–5.8	13K013	172.5	154.9	17.6
11H007	118.7	123.6	–4.9	14K008	190.6	191.3	–.7
13H007	153.2	146.3	6.9	12K009	142.2	135.3	6.9
08H007	144.3	135.6	8.7	12K014	41.9	35.2	6.7
07H015	149.4	129.2	20.2	13K017	164.4	157.4	7.0
05J007	173.4	167.0	6.4	13K018	177.6	182.9	–5.3
11J001	120.3	122.3	–2.0	08K008	219.2	220.1	–.9
09J009	135.9	136.3	–.4	12K013	141.0	148.0	–7.0
11J018	119.8	121.1	–1.3	15K010	216.5	215.8	.7
09J005	135.5	135.6	–.1	13K014	148.7	148.1	.6
11J006	115.4	116.4	–1.0	11K015	152.7	146.3	6.4
11J019	118.8	122.9	–4.1	12K016	144.5	150.8	–6.3
07J013	160.3	145.3	15.0	13K011	162.6	150.3	12.3
08J015	158.7	149.0	9.7	14K011	207.1	205.3	1.8
10J006	126.8	128.7	–1.9	08K007	218.7	218.8	–.1
10J005	130.0	136.4	–6.4	08K006	210.9	210.9	0.0
13J001	159.5	168.4	–8.9	10K005	177.9	166.4	11.5
09J010	139.2	122.8	16.4	13K019	148.4	143.9	4.5
11J012	116.9	115.4	1.5	14K012	221.6	220.7	.9
10J003	129.5	127.3	2.2	14K009	180.8	190.7	–9.9
09J004	143.4	130.6	12.8	11K003	157.1	158.6	–1.5
11J016	123.2	120.7	2.5	15K009	222.4	221.9	.5
11J005	124.4	120.9	3.5	14K006	207.9	212.4	–4.5
12J002	136.0	134.5	1.5	11L019	168.5	161.5	7.0
07J012	173.3	155.7	17.6	14L013	212.4	210.7	1.7
09J002	146.5	137.8	8.7	13L048	172.9	173.6	–.7
09J008	144.4	134.0	10.4	13L028	167.5	165.7	1.8
09J003	153.5	138.4	15.1	13L033	164.5	157.4	7.1
14J021	186.3	184.6	1.7	16L019	220.5	212.5	8.0
11J014	132.2	136.1	–3.9	13L012	156.1	148.9	7.2
08J004	171.1	187.8	–16.7	11L014	181.0	176.5	4.5

Footnote at end of table

Table A1. Ground-water-level residuals from calibrated Upper Floridan model of the lower Apalachicola-Chattahoochee-Flint River Basin

[Water-level altitude and residual, in feet above sea level]

Well number	$h_{i\ model}$[1] Computed water–level altitude	$h_{i\ obs.}$[1] Measured water–level altitude	Water–level residual	Well number	$h_{i\ model}$[1] Computed water–level altitude	$h_{i\ obs.}$[1] Measured water–level altitude	Water–level residual
12L030	153.4	151.0	2.4	13M057	210.1	215.6	–5.5
15L020	228.2	217.3	10.9	13M062	220.6	217.6	3.0
13L032	164.8	154.9	9.9	13M049	210.9	212.9	–2.0
12L023	159.0	145.8	13.2	13M080	229.9	230.3	–0.4
11L020	185.2	183.9	1.3	12M028	198.3	193.1	5.2
12L028	164.9	159.6	5.3	15M004	257.0	259.1	–2.1
14L012	221.2	222.9	–1.7	13M004	224.5	226.0	–1.5
13L003	174.7	182.2	–7.5	13M050	213.8	209.8	4.0
13L057	166.9	151.4	15.5	12M012	211.7	203.8	7.9
12L029	155.3	139.1	16.2	13M059	224.9	232.5	–7.6
11L022	196.3	182.6	13.7	12M004	208.4	204.6	3.8
14L009	225.9	233.1	–7.2	12M011	202.9	194.7	8.2
14L011	207.5	208.6	–1.1	13M079	230.5	227.7	2.8
13L049	162.3	164.2	–1.9	13M051	221.5	221.1	.4
10L004	212.5	218.9	–6.4	13M077	220.5	219.3	1.2
11L003	204.8	199.7	5.1	11M019	252.4	247.3	5.1
15L022	237.7	241.6	–3.9	14M008	246.6	250.2	–3.6
11L018	193.1	193.4	–.3	13M006	217.0	219.7	–2.7
13L014	168.2	174.0	–5.8	13M078	225.2	228.2	–3.0
11L021	197.2	188.4	8.8	14M006	227.0	230.5	–3.5
12L044	158.4	166.7	–8.3	13M066	217.7	216.6	1.1
11L017	196.7	190.0	6.7	13M060	224.7	225.5	–.8
13L052	170.4	183.9	–13.5	13M009	225.4	227.6	–2.2
13L047	203.5	195.1	8.4	10N013	292.5	293.6	–1.1
13L054	181.1	176.0	5.1	10N012	295.0	293.5	1.5
12L045	172.9	178.4	–5.5	12N003	233.6	240.7	–7.1
13L059	173.4	180.5	–7.1	12N005	223.9	223.8	.1
13L055	191.2	183.6	7.6	12N002	232.8	240.6	–7.8
12L043	177.0	182.4	–5.4	13N003	231.6	237.9	–6.3
15L023	241.1	247.5	–6.4	13N005	242.3	250.9	–8.6
14L014	230.2	234.8	–4.6	13N004	241.7	242.6	–.9
13M081	181.6	185.7	–4.1	13N009	255.4	264.2	–8.8
13M013	186.6	202.3	–15.7	13N007	259.3	255.0	4.3
12M017	89.4	79.4	10.0	12N004	263.1	263.1	0.0
11M010	210.7	209.0	1.7	13P005	262.5	258.6	3.9
10M003	228.1	230.8	–2.7	11P006	280.3	276.4	3.9
13M083	199.2	212.1	–12.9	12P012	268.7	273.2	–4.5
11M006	224.3	231.6	–7.3	13P004	266.0	273.0	–7.0
13M061	209.6	207.8	1.8	12P011	284.1	280.2	3.9
13M063	214.7	212.0	2.7	12P010	281.2	272.3	8.9
15M005	250.4	251.7	–1.3	15P002	275.3	273.3	2.0
13M008	207.3	212.6	–5.3	15P018	265.2	263.5	1.7
11M007	228.3	245.3	–17.0	14P013	240.0	230.7	9.3
14M009	211.5	222.0	–10.5	14P001	238.4	229.4	9.0
12M010	202.7	193.6	9.1	14P012	258.2	243.6	14.6
12M025	197.7	183.0	14.7	15Q011	277.5	284.0	–6.5

[1] $Average\ residual = \frac{1}{N}\sum_{i=1}^{N}\left(h_{i\ model} - h_{i\ obs}\right) = 0.4\ ft;\ N = 284.$

Table A2. Ground-water-level residuals from calibrated Intermediate model of the lower Apalachicola-Chattahoochee-Flint River Basin

[Water-level altitude and residual, in feet above sea level]

Well number	$h_{i\ model}$[1] Computed water-level altitude	$h_{i\ obs.}$[1] Measured water-level altitude	Water-level residual
CAL003	26.5	29.0	-2.5
CAL004	25.5	30.0	-4.5
CAL005	32.4	34.0	-1.6
FRA001	7.4	3.0	4.4
FRA002	5.1	9.0	-3.9
FRA003	8.9	2.0	-3.1
FRA004	8.8	15.0	-6.2
GUL001	-0.8	-2.0	1.2
GUL002	7.8	10.0	-2.2
GUL003	8.0	-2.0	10.0
GUL004	11.0	7.0	-6.0
GUL005	16.3	18.0	-1.7
GUL006	16.4	21.0	-4.6
GUL008	15.3	15.0	0.3
GUL009	18.3	22.0	-3.7
LIB001	39.6	34.0	5.6
LIB002	37.9	34.0	3.9
LIB003	14.6	10.0	4.6
LIB004	29.9	31.0	-1.1

[1] $Average\ residual = \frac{1}{N}\sum_{i=1}^{N}\left(h_{i\ model} - h_{i\ obs}\right) = 0.6\ ft;\ N = 19.$